

drilling fluids technology

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The following information is not included in this manual at this time. Please refer to the hard copy for the following information. It will be added at a later date.

Appendix H - Drilling Fluid Specifications and Testing	Standard Procedure for Testing and Drilling Fluids
	Oil-Well Drilling Fluid Materials
	API Recommended Practice 13B-1 (RP 13B-1) First Edition, June 1990 <i>Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids</i>

Section I

Introduction

Introduction

The drilling fluid is related either directly or indirectly to almost every drilling problem. This is not to say that the drilling fluid is the cause or solution of all drilling problems, but it is a tool that can often be used to alleviate a problem situation.

Many have thought that a magic additive would solve all of their problems and that the drilling fluid could somehow make up for poor drilling practices. This is simply not the case. It is a part of the drilling process and should be used to complement all other facets of the operation. Selection and application of the drilling fluid are key factors in the success of any drilling operation.

The first objective in planning a mud program is the selection of a mud that will minimize the amount of lost time in the drilling operation. Such a mud will usually be economical regardless of its cost per barrel.

Generally, a good drilling fluid is simple and contains a minimum number of additives. This allows easier maintenance and control of properties. It is desirable to have a mud system that is flexible

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Introduction

Continued

enough to allow changes to be made to meet changing requirements as they occur. Each change in the mud should be planned well in advance of the time it is required. This will allow current treatment of the mud consistent with future requirements.

Planning of the mud program begins with acquisition of all pertinent geologic and offset well information. This includes pore pressure and fracture gradient profiles, formation characteristics, intervals of possible borehole instability, location of soluble salt beds, and the possibility of sour gas or saltwater flows. Good information is an absolute necessity for good engineering. This necessitates communication between those persons concerned with the different parts of the operation.

Next, the mud and casing programs should be integrated. The only solution to some problems is to isolate them behind casing. This is especially true when two problems that require opposite mud properties occur at the same time. For instance, a lost-returns zone and a high-pressure sand or sloughing shale open at the same time lead to a conflict that cannot be resolved by the mud alone. The mud program should be planned for each casing interval with a contingency plan for deviations from the casing Program.

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Introduction

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After selection of a suitable mud program, consideration should be given to its implementation. The performance of a drilling fluid is determined more by engineering than by the products used. Exotic mud systems, which are not understood by those running them, often result in failure.

In selecting a mud company, first consideration should be given to the technical ability of the personnel who will be working the job and the backup support they can expect to receive. There are few instances where the quality and performance of their products are more important than the technical and logistical services that they perform. The cost of products is also important, but should be considered only on a cost-performance basis. Our objective is to minimize overall drilling, evaluation, and completion costs.

Running a mud system consists primarily of controlling the type and amount of solids in the mud and their chemical environment. All mud properties are controlled by controlling these compositional factors. Consequently, an adequate solids control program should be a part of every mud program.

The rig mud facilities should be designed to provide for proper arrangement of solids control equipment and mud mixing equipment. Rigs with single mud pits make mud treating and solids control especially ineffective. Inadequate rig mud facilities are often responsible for a considerable amount of lost time, poor mud properties, and increased mud costs.

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Introduction

Continued

Accurate mud tests are necessary for proper control of the mud properties. Good working conditions for performing these tests are essential. On critical wells, a separate mud trailer would be desirable. In any case, attention should be given to providing adequate, protected space with good lighting.

We cannot have a successful drilling operation unless all facets of it are well planned and executed. This includes proper application of the drilling fluid.

Every Drilling Superintendent and Drilling Engineer should be knowledgeable in drilling fluid technology and able to apply this technology to the drilling operation. He should be able to evaluate and control the performance of a mud.

This book is intended to serve as a guide to drilling fluid technology. It is not intended to be a "cookbook", but rather to provide general information on the basic principles of mud technology.

Section II

FUNCTIONS OF A DRILLING FLUID

Functions of a Drilling Fluid

There are a number of functions of a drilling fluid. The more basic of these are listed below:

1. Balance formation pressure
2. Carry cuttings and sloughings to the surface
3. Clean beneath the bit
4. Cool and lubricate bit and drill string
5. Seal permeable formations
6. Stabilize borehole
7. Corrosion control

In addition to these functions, there are several other functions with which the drilling fluid should not interfere:

1. Formation evaluation
2. Completion operations
3. Production operations

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Functions of a Drilling Fluid

Continued

Clearly, these lists of functions indicate the complex nature of the role of drilling fluids in the drilling operation. It is obvious that compromises will always be necessary when designing a fluid to carry out these functions, which in some cases require fluids of opposite properties. The most important functions in a particular drilling operation should be given the most weight in design of the drilling fluid.

Many of these functions are controlled by more than one mud property and should be discussed in more detail.

Pressure Control

The density of drilling fluid must be such that the hydrostatic pressure exerted by the mud column will prevent flow into the wellbore. This is the first requirement of any drilling fluid and it must be provided for before considering any other mud property or function. The equation for calculating hydrostatic pressure is:

Hydrostatic Pressure, psi = (depth, ft.)(mud weight, lb./gal)(0.052)

Pressure control would be rather simple if it consisted only of balancing the hydrostatic and formation pressures in the static condition. However, pressure is required to cause a fluid to flow. This pressure is dissipated in frictional losses along the entire flow

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Pressure Control Continued

path. Consequently, the total pressure at any point in a circulating system is the sum of the hydrostatic pressure at that point and in the circulating pressure drop from that point to the exit point. Under normal circulating conditions, the pressure at any given point in the hole is the sum of the hydrostatic pressure at that point and the circulating pressure drop from that point to the flow line. An example of circulating pressures at various points in the system is seen in **Figure 1**.

When pipe is run into the hole, the pipe displaces fluid, causing it to flow up the annulus. This is analogous to circulating the fluid and pressure calculations can be made in the same manner. When pipe is being pulled from the hole, the mud falls under its own weight to fill the void volume left by the pipe. The mud flowing down the annulus under gravity develops a flowing pressure drop that subtracts from the hydrostatic pressure. The total pressure at any point in the annulus is the hydrostatic minus the flowing pressure drop from the surface to that point in the annulus.

Figure 2 illustrates pressure profiles under swab, static, or surge conditions. The difference in total pressure at any depth between the hydrostatic and swab or surge lines is the pressure drop caused by pipe movement.

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Figure 1

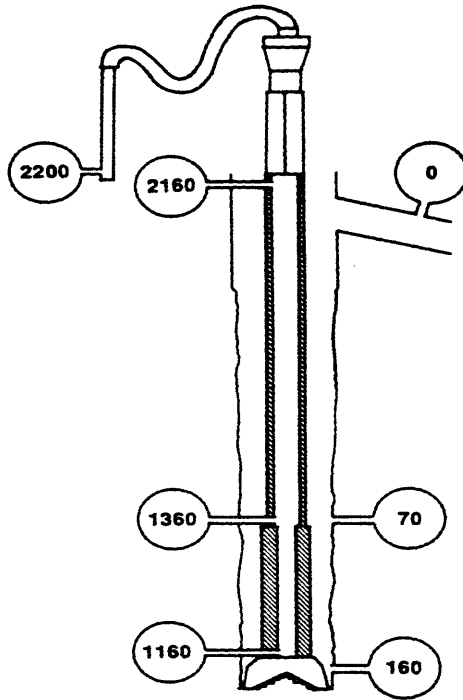
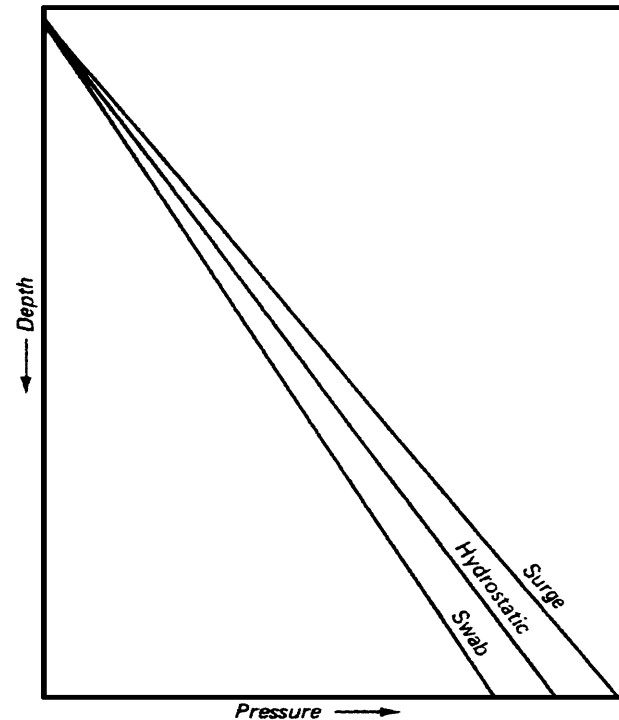


Figure 2



Pressure Control Continued

Obviously, if a formation pressure is greater than the wellbore pressure under swab conditions, the formation fluid will flow into the well when the pipe is pulled. If the fracture pressure of a formation is less than the pressure at that depth under surge conditions, the formation will be fractured while running the pipe and lost circulation will occur. These factors must be taken into account when establishing the required density of a mud.

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Pressure Control

Continued

Normally the mud density will be run slightly higher than required to balance the formation pressure under static conditions. This allows for a safety margin under static conditions and offsets the same amount of negative swab pressure. If the swab effect is still greater than the overbalance, it must be reduced by slower pipe pulling speeds. This is necessary because further increases in mud density would cause problems in the areas of lost circulation, decreased penetration rates, and differential pressure sticking. The hole must be filled when pulling pipe to replace the volume of the pipe. Otherwise, the reduction in hydrostatic pressure will allow the well to flow.

By the same token, if the surge or the circulating pressure drop causes the total pressure to exceed the fracture pressure of a formation, the pipe running speed or the circulating rate must be decreased enough to prevent fracturing from occurring. When it becomes impossible to meet minimum and maximum pressure requirements at realistic pipe moving speeds or circulating rates, it is time to case the hole.

There are at least two different ways of calculating the annular pressure loss while circulating a mud. One method is to measure or predict the mud flow properties under downhole conditions and knowing the circulation rate and hydraulic diameter, calculate directly the annular pressure drop.

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Pressure Control

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This method has several weaknesses. First, an accurate knowledge of the flow properties of the mud is usually not available. This is especially true of water-base muds, which tend to gel with time when static in the hole and gradually decrease in viscosity when sheared. Such a mud may have a considerably higher gel strength and yield point initially after breaking circulation than under normal circulating conditions. Annular pressure drop calculations using flow line measurements of mud properties will yield pressure losses that are less than actual when the mud is gelled downhole.

A second problem with annular pressure drop calculations is in knowing the hole diameter. If the hole is washed out, the pressure drop will be less than calculated; if a filter cake is deposited, the diameter will be decreased and the pressure drop greater than calculated. We are normally faced with estimating the average hole diameter in order to calculate pressure drop.

The clearance between pipe and hole is very critical to pressure drop when this clearance is small. For this reason we need an accurate estimate of hole size around the drill collars. Fortunately, this is the part of the hole that should be least washed out and has the thinnest filter cake.

A third factor that leads to inaccuracy in annular pressure drop calculations is how well the pipe is centered in the hole. Our calculation procedure assumes perfect centering. This is usually not

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Pressure Control

Continued

the case. The pressure drop in the annulus is greatest when the pipe is centered and is least when the pipe is lying against the wall. This means that we tend to calculate a pressure drop which is higher than actual.

In general, this method of determining annular pressure loss is accurate for oil muds, which are not susceptible to temperature elation and which tend to keep the hole in gage. The method is not so accurate for water muds and especially for those which have high gel strength at bottom hole temperature.

A second and more accurate method for determining annular pressure losses employs the use of an accurate standpipe pressure measurement. The pressure drop down the drill string and through the bit can be accurately calculated with a Reed Slide Rule and subtracted from the standpipe pressure. The difference is the pressure drop up the annulus. This method is also quite useful while breaking circulation and until "bottoms up" has been obtained. During this period, the flow properties of the mud downhole are unknown and changing rapidly. This makes the direct calculation of annular pressure drop quite inaccurate.

After breaking circulation, the annular pressure drop will decrease for a period of time. This is due to "shearing down" the gel structure of the mud. However, the shear rate in the annulus is not high

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Pressure Control

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enough to break all flocculation bonds and the “bottoms up” mud will remain abnormally high in viscosity. As this mud becomes cooler, as it is circulated up the hole, the viscosity will begin to increase. When the “bottoms up” mud is somewhere in the upper half of the hole, the pressure drop may begin increasing. If the circulation rate is not decreased, a pressure drop greater than that required to initiate circulation may occur.

A detailed analysis of pressure drop calculations is given in **Appendix A**. Remember that these are calculations and the answers are only as good as the input data. Always try to determine how the most probable errors in the input data will affect your answer and how this will affect the drilling operation.

Hole Cleaning

The ability to lift particles of various sizes out of the hole is one of the most important functions of a drilling fluid. This is the only way that the rock which is drilled or which sloughs from the wall is carried out of the hole. In a 12 1/4-inch hole, about 130 pounds of earth material must be removed for every foot of hole drilled. In fast drilling an enormous amount of drilled cuttings are entering the mud system. The mud circulation rate must be high enough to prevent an excessive increase in mud density or viscosity.

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Hole Cleaning Continued

Drilling a 12 ¼-inch hole at 3 feet per minute while circulating a 9 lb./gal mud at 10 bbl/min will result in a mud density increase in the annulus to 9.5 lb./gal. If the drilled solids are fine and further dispersed into the mud, a substantial increase in viscosity will result. The combination of these two effects may cause the equivalent circulating density of the mud in the annulus to exceed the fracture gradient and cause loss of circulation. The circulation rate can be increased to minimize the increase in density and viscosity due to the influx of solids, but this will also cause an increase in equivalent circulating density. If this ECD is also higher than fracture gradient, then the drilling rate must be decreased.

It is possible, for short periods of time, to obtain such high drilling rates in soft shales that cuttings cannot be wet and dispersed fast enough to prevent them from sticking together and forming "balls" or "slabs". For this reason, it is necessary to watch not only the long time average drilling rate but also the instantaneous rates. A procedure for calculating annular mud density increase due to drilled solids influx is given in **Appendix A**.

Another, more common type of carrying capacity problem is the ability of the fluid to lift the cuttings or sloughings and carry them out of the hole. This problem is often difficult to detect because some of the smaller cuttings come out while the larger ones remain in the

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Hole Cleaning

Continued

hole. If the hole is beginning to slough, the amount of shale coming across the shaker will appear to be normal, but large amounts may be collecting in the hole. Sometimes the appearance of the cuttings will indicate poor hole cleaning. If the cuttings are rounded, it may indicate that they have spent an undue amount of time in the hole.

The condition of the hole is usually the best indicator of hole cleaning difficulty. Fill on bottom after a trip is an indicator of inadequate cleaning. However, the absence of fill does not mean that there is not a hole cleaning problem. Large amounts of cuttings may be collecting in washed-out places in the hole. Drag while pulling up to make a connection may also indicate inadequate hole cleaning. When the pipe is moved upward, the swab effect may be sufficient to dislodge cuttings packed into a washed-out section of the hole. The sudden dumping of even a small amount of material is often enough to cause severe drag or sticking.

Hole cleaning is a more severe problem in high-angle holes than in vertical holes. It is not only more difficult to carry the cuttings out of the hole, but they need to settle only to the low side of the hole before causing problems. Consequently, more attention should be paid to hole cleaning requirements in directional holes.

The ability of a fluid to lift a piece of rock is affected first by the difference in density of the rock and the fluid. If there is no difference in densities, the rock will be suspended in the fluid and

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Hole Cleaning

Continued

will move in a flow stream at the same velocity as the fluid. As the density of the fluid is decreased, the weight of the rock in the fluid is increased and it will tend to settle. The shear stress of the fluid moving by the surface of the rock will tend to drag the rock with the fluid. The velocity of the rock will be somewhat less than the velocity of the fluid. The difference in velocities is usually referred to as a slip velocity. The shear stress that is supplying the drag force is a function of shear rate of the fluid at the surface of the rock and the viscosity of the mud at this shear rate. A number of other factors such as wall effects, inter-particle interference, and turbulent flow around the particles make exact calculations of slip velocity impossible. However, equations for estimating slip velocities are shown in Appendix G. These equations give a rough idea of the size range that can be lifted under a given set of conditions.

In general, hole cleaning ability is enhanced by the following:

1. Increased fluid density
2. Increased annular velocity
3. Increased YP or mud viscosity at annular shear rates.

It should be noted that with shear thinning fluids it is sometimes possible to decrease annular velocity, increase the yield point, and also increase the hole cleaning. This is done in order to minimize hole erosion. Where viscosity is sufficient to clean the hole, the

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Hole Cleaning

Continued

annular velocity should be maintained below that for turbulent flow in order to minimize annular pressure drop and hole erosion. This, of course, is not possible when drilling with clear water where high velocities and turbulent flow are usually necessary to clean the hole.

Cleaning Beneath the Bit

Cleaning beneath the bit appears to require mud properties almost opposite from those required to lift cuttings from the hole. In this case we want the mud to have as low a plastic viscosity as possible. Since the fluid shear rates beneath the bit are at least 100-fold greater than in the annulus, it is possible to have low viscosities at the bit and sufficient viscosity in the annulus to clean the hole. A mud that is highly shear-thinning will allow both functions to be fulfilled. Flocculated mud and some polymer muds have this characteristic.

Since cleaning beneath the bit relates to penetration rate, all other factors that relate to penetration rate (such as density, hydraulics, etc.) should be considered simultaneously.

Cooling and Lubricating

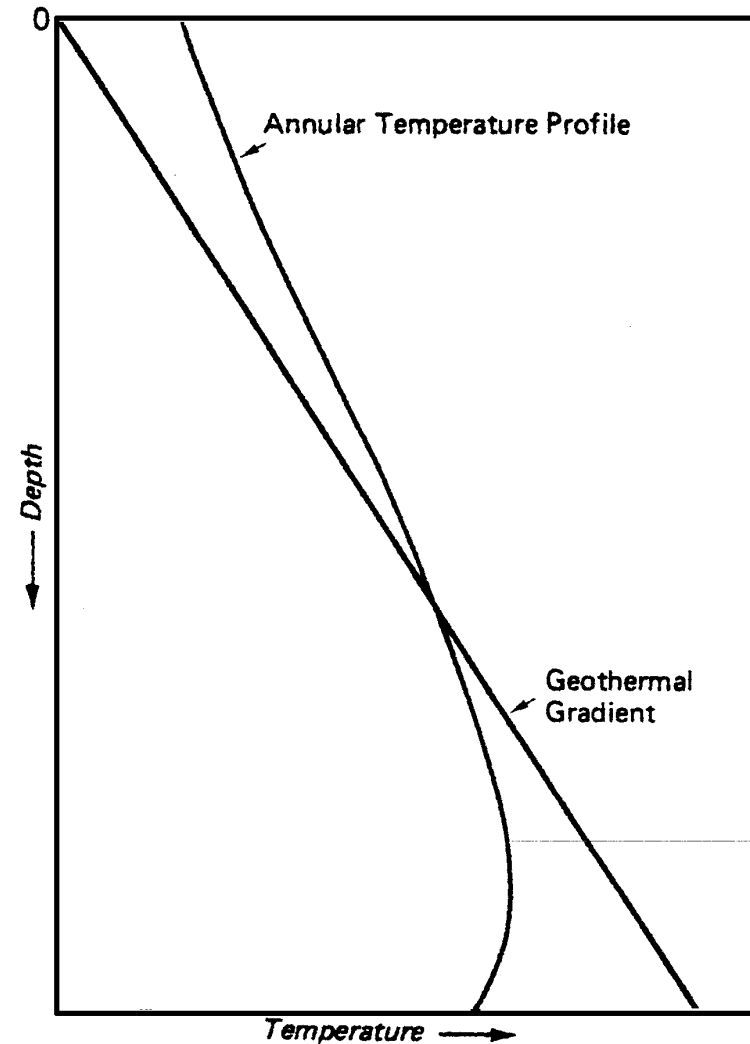
Cooling and lubricating the bit and drill string are done automatically by the mud and not because of some special design characteristic. Muds have sufficient heat capacity and thermal conductivity to allow heat to be picked up down hole, transported to the surface, and dissipated to the atmosphere.

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Cooling and Lubricating Continued

The process of circulating cool mud down the drill pipe cools the bottom of the hole. The heated mud coming up the annulus is hotter than the earth temperature near the surface and the mud begins to heat the top part of the hole. This causes the temperature profile of the mud to be different under static than under circulating conditions, as shown in **Figure 3**.

Figure 3
Circulating Temperature Profile



Cooling and Lubricating

Continued

The maximum mud temperature when circulating is cooler than the geothermal bottom-hole temperature. The point of maximum circulating temperature is not on bottom but about a third of the way up the hole. These facts are important to remember when attempting to predict mud behavior downhole. A mud additive which is not completely stable at the geothermal bottom-hole temperature may perform adequately at the circulating temperatures. If flocculation due to temperature begins to occur during circulation, as evidenced by increases in yield point and gel strength at the flow line, then we can be assured that severe gelation will occur as the mud heats up after circulation is stopped.

In addition to cooling the well bore, the circulating mud also removes frictional heat and supplies a degree of lubrication. Cooling is especially important at the bit where a large amount of heat is generated. Sufficient circulation to keep the temperature below a critical point is essential in using a diamond bit.

Lubrication is a very complex subject and especially as it applies to the drilling operation. If a mud does not contain a great deal of abrasive material such as sand, it will supply lubrication to the drill string simply because it is a fluid that contains solids that are softer than the pipe and casing. Attempts to improve this basic lubricating quality of a mud are usually ineffective and expensive. Probably far greater benefits can be realized by keeping the abrasive content of a mud as low as possible.

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Cooling and Lubricating

Continued

Hole symptoms such as excessive torque and drag, which are often associated with the need for a lubricant in the mud, are often caused by other problems such as bit or stabilizer balling, key seats, and poor hole cleaning. Sometimes materials sold as lubricants relieve these symptoms, but not as cheaply or effectively as a more specific solution to the problem.

The success or failure of a lubricant is related to its film strength in relation to the contact pressure at the surface being lubricated. If the lubricating film is "squeezed out", then the lubricant has apparently failed. A material that appears to be a good lubricant in a test at low contact pressure may fail in actual application due to higher contact pressures, higher rotating speed, etc. The only good test of a lubricant is under the exact conditions that exist where lubrication is desired. Unfortunately, these conditions are not known downhole.

Lubrication should not be confused with attempts to reduce differential pressure sticking. These are two different problems. Additives sold as lubricants will probably do very little to relieve differential pressure sticking if used in the concentrations recommended for lubrication.

Seal Permeable Formations

When drilling with clear water, there is no provision for sealing permeable formations. The use of clear water is practical only when these conditions exist:

1. The exposed formations do not have enough permeability to allow a significant flow of water into the formations.
2. The differential pressure from borehole to formation is not sufficient to cause a significant flow of water into the formations.
3. The amount of water lost to a formation is not important from a formation evaluation standpoint.
4. There are no unconsolidated sands that need to be strengthened by deposition of a filter cake.
5. Density and hole cleaning requirements do not necessitate building a mud.

When solids are added to a clear fluid, they will deposit on the wall of permeable formations as the fluid flows into the formation, and thus begin to retard the flow of the fluid. As the solids cake grows thicker, the rate of flow into the rock decreases. In this manner, a degree of sealing occurs. This decreases the amount of fluid that is lost to a formation, but at the same time filter cake buildup causes other problems. For this reason, the filtration characteristics of most muds are measured and controlled.

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Seal Permeable Formations

Continued

Functionally, a mud must keep the loss of fluid to a formation small enough to prevent excessive flushing of the resident fluid away from the well bore. It must also prevent deposition of excessive thick filter cakes. This function is the most difficult to provide and also the most important from a drilling operations standpoint.

Thick filter cakes are the source of several types of drilling and completion problems. Probably the one problem that is most directly associated with thick filter cakes is differential pressure sticking. As the cake thickness is increased, the contact area of pipe in the cake is increased and the sticking force is increased. With thin, low-permeability filter cake, the probability of pipe sticking is greatly reduced.

Another major type of problem that is not normally associated with thick filter cakes is that of lost circulation. If there is an appreciable amount of permeable formation covered with thick filter cake, the circulating pressure drop will be increased due to the decreased clearance between the wall and the pipe. Increased swab pressures will exist and increased pressure surges will be an even greater problem since the cake will grow thicker under the static conditions that exist during a trip.

Logging difficulties are also caused by thick filter cakes. The responses of some logging tools are altered by a thick cake, the

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Seal Permeable Formations

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possibility of sticking the tools is increased, and in some cases the tools will not go down because of drag on a thick cake.

A number of other problems, such as torque and drag, difficulty in running casing, and poor cement jobs, can be caused by thick filter cakes.

In short, sealing the walls of the borehole is more involved than simply reducing the amount of filtrate that enters the rock. In most cases, this is incidental to the primary aim of maintaining as thin and impermeable a cake as possible.

Stabilize Borehole

The borehole walls are normally competent immediately after being drilled. No collapse or sloughing will occur if the formation pore pressure is balanced; in many cases, a considerable under-balance can be tolerated. There are a few exceptions to this rule, but in general instability of the borehole is caused by reaction with the drilling fluid. More specifically, most instability is caused by water being absorbed by shale.

Absorption of water has two effects that combine to cause failure of the rock. First, absorption induces a stress in the rock. As more and more water is absorbed the stress grows until it overcomes the strength of the rock. The stress is then relieved by failure of the rock. The second effect of the absorbed water is to weaken the

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Stabilize Borehole

Continued

shale. Again, as more water is absorbed, the rock becomes weaker and the stress becomes greater. The weakening accelerates the occurrence of rock failure.

The wellbore stress is balanced in part by the hydrostatic pressure in the wellbore. If absorption of water has increased the stress and weakened the rock to the point of failure, increased mud density will counteract part of this stress and prevent rock failure. More water absorption will continue to increase the stress imbalance and weaken the rock until failure occurs once more. For this reason, increased mud density is only a temporary deterrent to most shale sloughing.

The only complete answer to shale sloughing is to prevent absorption of water. Balanced-activity oil muds are presently the only means of completely preventing absorption of water in shales.

Special water muds in which the electrolyte content has been adjusted to minimize the reactivity with a specific type of shale, can slow the rate of absorption and thus delay the onset of sloughing. These types of muds are not universal in their ability to reduce sloughing in all types of shales.

Since the absorption of water is not controlled by the filtration characteristics of a mud, reduced filtration should not be a criteria for a shale control mud. Some contend that water penetration into

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Stabilize Borehole

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some shales is through microfractures or permeable seams. If this is true, it would be controlled by a plugging action, not to be confused with filtration control.

In general, reduction of water absorption is the most important means of control of shale sloughing. This includes both rate of absorption and time of exposure. If the rate cannot be controlled by practical application of the right type of mud, then the time of exposure of the shale to the mud must be reduced. This means drilling the shale and getting it behind casing as quickly as possible. Increasing mud density can buy some extra time, ranging from a few hours to a few days. This is a last resort practice since it brings with it other problems.

In some cases, increased mud density must be used. These are cases, such as abnormal pressure zones, where the initial stress exceeds rock strength unless that stress is partially counteracted by increased hydrostatic pressure.

Reduction of fluid loss of a mud is not a justifiable means of shale control. The use of materials that plug or coat may or may not be beneficial in particular situations. The effects of these materials are largely unproven. They certainly do not have universal application.

Most mud additives, which supposedly aid in control of hole stability, do not reduce shale sloughing. They do aid in removal of the

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Stabilize Borehole

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sloughed shale, reduce erosion effects, or slow the rate of disintegration and dispersion of the shale particles into the mud. In other words, these additives are remedial but do not work on the basic problem. There are times when this type of control is adequate to handle our drilling problems. In these cases, we are able to live with an enlarged hole by supplying additional carrying capacity in the mud.

There are a number of purely mechanical aspects of hole stability. Erosion by the drilling fluid is a factor in hole enlargement. It may be the “last straw” which causes an already weakened piece of shale to slough. Erosional effects can be minimized by reducing the annular velocities to change the flow regime from turbulent to laminar. Action of the drill string may also cause sloughing by pipe buckling, “digging in” of stabilizers, etc. A smooth, stiff bottom-hole assembly may aid in preventing this type of mechanical action on the wellbore.

Swabbing is another means of causing an already unstable zone to slough. Swabbing causes a reduction in hydrostatic pressure, which increased the stress imbalance at the wall. This may be sufficient to cause sloughing. While swabbing, the fluid motion is down the wellbore, which is a change from normal. This may have the effect of dislodging pieces of rock into the wellbore. These pieces could be

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Stabilize Borehole Continued

either a part of the wall or have previously sloughed and been packed into a washed-out interval. In either case, swabbing may give rise to what has been a dormant problem.

Corrosion Control

Corrosion is a reaction of metal with its environment. We are concerned here with corrosion of tubular goods in a drilling fluid. The drilling fluid may not be basically corrosive, but it can become corrosive when common contaminants such as oxygen, carbon dioxide, and hydrogen sulfide are incorporated in it. Oxygen, and to a limited degree carbon dioxide, are incorporated into the mud as it circulates through the surface mud system. Hydrogen sulfide, carbon dioxide, and occasionally organic acids can become incorporated in the mud from formations drilled, bacterial action, and degradation of certain mud additives. The drilling fluid is a carrier of agents that promote corrosion; in like manner, the fluid can become a carrier of materials that will counteract these agents and retard corrosion. Thus, corrosive agents introduced into the wellbore from the formation can be neutralized by the mud before they cause serious problems.

We normally think of corrosion as the process which causes pitting and simple metal loss to occur. Oxygen is the principal culprit so far as corrosion of the drill assembly is concerned.

Continued on next page

Corrosion Control Continued

The only requirements for corrosion are an anode, a cathode, and contact with an electrolytic fluid to carry the current flow. The anode and cathode can occur on separate pieces of metal or on the same piece at different points. The anode is the point where corrosion occurs. Water muds are a part of this corrosion cell in that they provide the electrolyte contact.

Hydrogen molecules collect at the cathode, forming an insulating blanket that reduces the current flow and retards the corrosive action. Dissolved oxygen will react with hydrogen to form water, thus preventing the protective action of the hydrogen film and re-establishing the corrosive action. Therefore, dissolved oxygen accelerates corrosion and is undesirable in a drilling fluid.

Figure 4 shows the effect of oxygen on corrosion rate of a mild steel coupon.

Solids and some organic additives in muds appear to limit the amount of oxygen available to accelerate corrosion. The absence of these materials from brines and other clear water drilling fluids makes corrosion problems especially bad in these fluids. Special oxygen scavengers such as sodium sulfite and hydrazine are sometimes used. Efforts should be made to minimize the aeration of mud in the surface system.

Continued on next page

Corrosion Control

Continued

Certain cationic organic film formers can also be used to extend the life of drill pipe. These inhibitors should not be added to a mud. They will react with the solids, becoming ineffective and causing mud problems. Various methods are used to get the corrosion inhibitor on the pipe rather than in the mud:

1. The drill pipe is sometimes dipped or sprayed with corrosion inhibitor solution before it is run in the hole.
2. Batches of inhibitor diluted to 5-10 parts by diesel oil are pumped down the drill pipe periodically. Such batch treatment of diluted inhibitor solutions might be 5-20 gallons pumped every 1 to 4 hours.
3. For better protection on the outside of the drill pipe, the pipe is pulled through a wiper and sprayed with inhibitor solution on trips out of the hole.

One of the most effective controls of corrosion is to maintain a high alkalinity in the drilling fluids. This has a double purpose. It slows the rate of corrosion and it reduces the rate of degradation of some organic mud additives (such as lignosulfonate) that produce corrosive by-products. The effects of pH on corrosion rate and corrosion fatigue are shown in **Figures 4 and 5**.

Significant decreases in corrosion rate are apparent at a pH above 10. The rate of degradation of lignosulfonate at high temperatures

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Figure 4

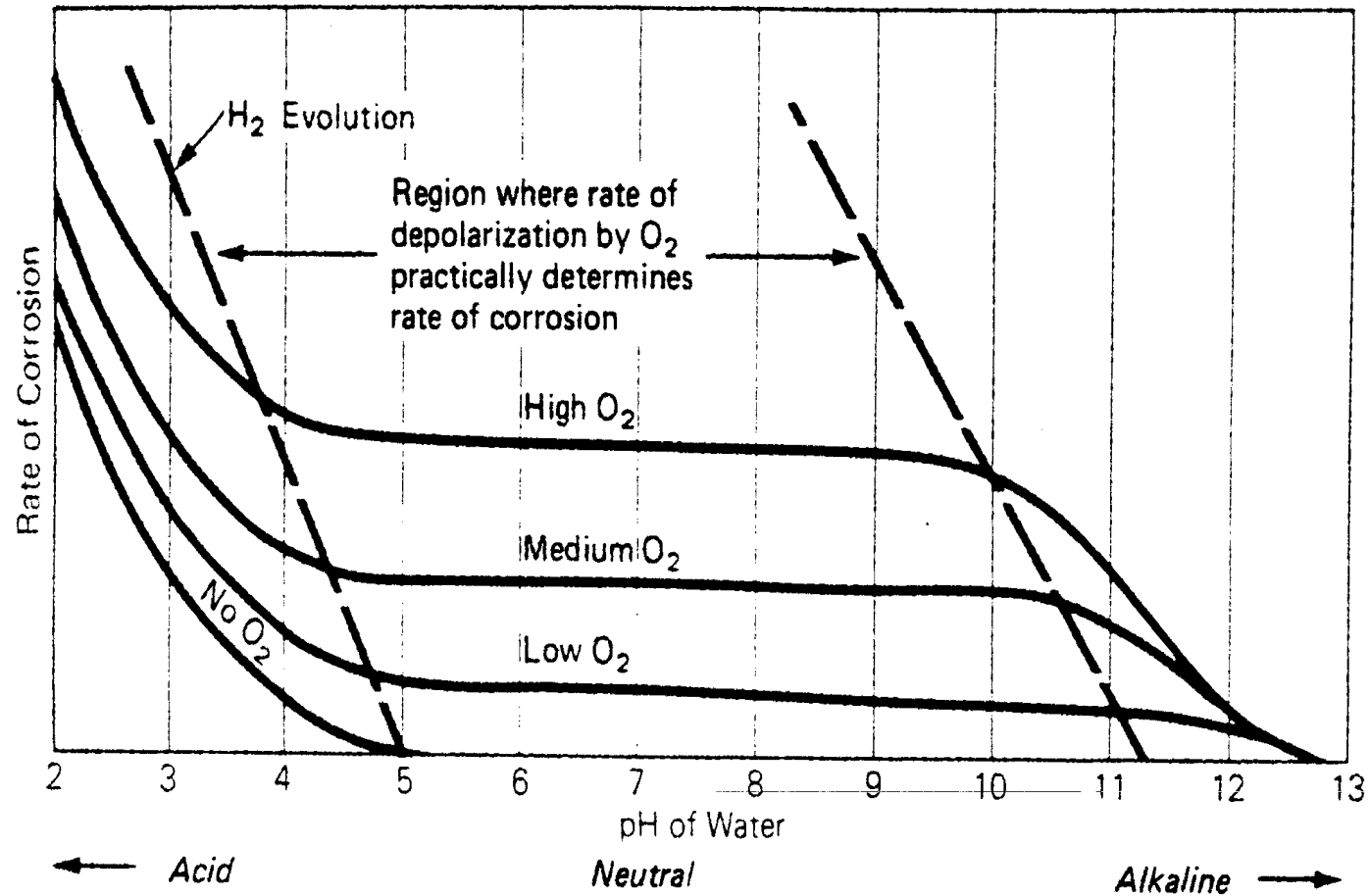
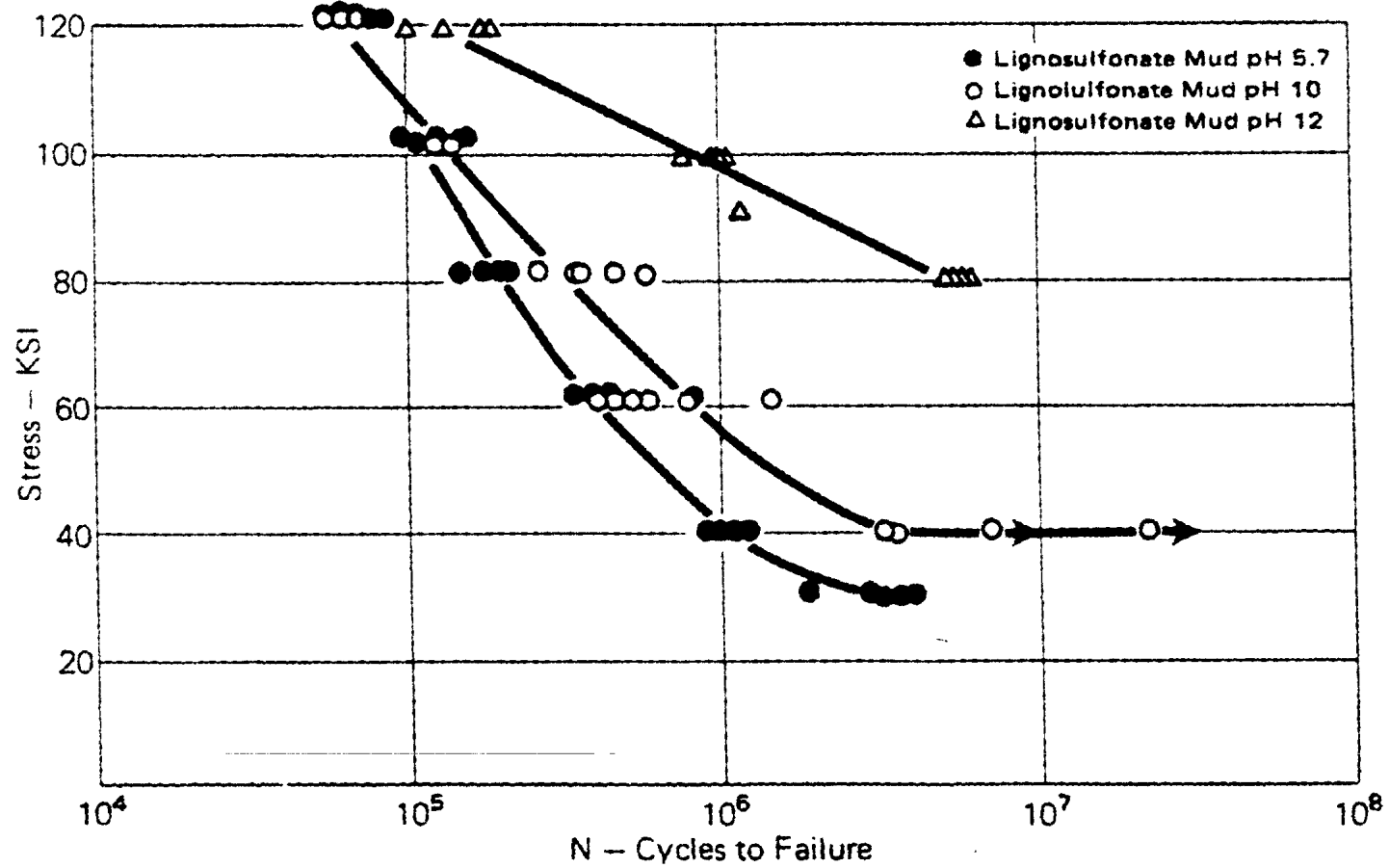


Figure 5
High pH Prevents Corrosion Fatigue



Corrosion Control

Continued

has also been shown to decline significantly at a pH above 10. For this reason, the use of caustic soda or lime is the most economical treatment of a water-base mud; if used properly, the treatment will greatly reduce major corrosion attack.

Hydrogen embrittlement is a type of corrosion that has become more prevalent in recent years. Deep drilling, the use of higher-strength steel, and drilling of formations containing hydrogen sulfide have combined to make this a major problem.

Hydrogen embrittlement is a process wherein atomic hydrogen, present in acid environment, actually penetrates and is absorbed by the steel. Once inside the steel, hydrogen atoms diffuse and seem to move to points of high tensile stress. When their passage through the steel is impeded, the atoms of hydrogen combine to form hydrogen gas. In the process of combination and expansion, the hydrogen molecules will crack the harder, finer-grained steels. Any acid-former can possibly provide the atomic hydrogen necessary for embrittlement. Acid gases such as hydrogen sulfide and carbon dioxide are frequent culprits in drill pipe embrittlement.

The tendency for hydrogen stress cracking in high-strength tubular goods is greatly reduced at elevated temperatures. It is believed that the increased temperature increases the mobility and diffusion rate

Continued on next page

Corrosion Control

Continued

of hydrogen and prevents its accumulation in the steel at points of stress. Temperatures above 150°F appear to reduce cracking, with the problem being virtually eliminated at 300°F.

An essential requirement for protecting high-strength pipe from hydrogen embrittlement is maintenance of the mud at high pH. This eliminates the development of an acid environment necessary for hydrogen embrittlement and quickly neutralizes the hydrogen ions.

Even though an influx of hydrogen sulfide may be neutralized by a high pH mud, the sulfide will remain soluble in the mud. If the mud later becomes acid; hydrogen sulfide will again be formed. In addition to being corrosive, hydrogen sulfide is highly toxic and must be eliminated from a mud for reasons of safety to personnel. To remove any possibility of hydrogen sulfide reforming in a mud, the soluble sulfides should be precipitated in an insoluble form. Addition of certain metal compounds of copper, zinc, and iron have been used for this purpose. Copper presents a secondary problem of causing metal loss corrosion when used in excessive concentrations. For this reason, the other metal compounds are preferred.

Thus far, this discussion of corrosion has been limited to water-base muds. The use of oil muds eliminates or greatly simplifies corrosion control problems. Since oil is the continuous phase, there is no

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Corrosion Control

Continued

electrolyte solution to carry current in a corrosion cell if the water in the oil mud is sufficiently well emulsified. Oil wetting agents in the mud keep the pipe wet with oil and provide corrosion protection even when the pipe is exposed to air. In an oil mud it is possible to carry high concentrations of lime to effectively neutralize acid gases. This greatly reduces the possibility of hydrogen embrittlement. If corrosion control were the only consideration, oil muds would be far superior to water muds.

Formation Evaluation

A drilling fluid must carry out its basic functions in the drilling operation while at the same time allowing retrieval of all necessary geologic and formation evaluation information. Normally, this does not present any problems that cannot be avoided by careful planning.

Both the formation evaluation and mud programs must be consistent with one another. Mud type, whether oil or water continuous, will alter the type of logs which can be run. The salinity of water-base muds as well as the degree of flushing of the zone around the wellbore are important evaluation considerations. The mud type and condition are important from the standpoint of mud logging and show detection. These problems should be discussed with well evaluation personnel before final selection of mud and evaluation programs.

Continued on next page

**Formation
Evaluation**
Continued

Filtrate, which invades a formation, displaces the formation fluid from around the wellbore. If the depth of filtrate invasion is greater than the depth of investigation of an electric logging tool, the log will give misleading information. A similar problem exists with a wireline test where only filtrate is recovered or with a drill stem test where unlimited filtration can distort interpretation of recovered fluids.

The depth of invasion is a function of the amount of filtrate lost, the porosity, and fingering of the filtrate due to heterogeneity of some formations. Nothing can be done about the last two factors. A low porosity and filtrate fingering may allow deep invasion, which will seriously affect formation evaluation despite our best efforts.

Due to the radial geometry involved, the depth of invasion increases as the square root of filtrate volume. In other words, a fourfold increase in filtrate volume will only double the depth of invasion. This shows that small changes in filtration rate will not appreciably affect the depth of invasion. Most of the problems of deep invasion are the results of little or no filtration control. When steps are taken to reduce filter cake thickness to solve drilling problems, filtrate invasion is no longer a major problem.

The volume of filtrate lost to a formation is primarily a function of the dynamic filtrate rate and the time of filtration under dynamic conditions. Therefore, any attempt to limit fluid loss to a formation should be aimed at reducing dynamic filtration.

Continued on next page

**Formation
Evaluation**
Continued

The dynamic filtration rate can be reduced by either reducing the annular velocity or increasing the colloidal solids content of the mud. Either method will cause the thickness of the filter cake to increase and thereby reduce the rate of filtration. Deposition of a static filter cake will also result in a thicker cake which from that time forward will limit the total fluid loss.

Fluid-loss control agents, which reduce the filter cake permeability and consequently the static fluid loss, have very little effect on the dynamic filtration rate. Therefore, API fluid loss should not be used as the criteria for limiting filtrate invasion.

Loss of whole mud in a pressure-induced fracture can lead to the same evaluation problems as deep filtrate invasion. Lost returns with an oil mud may completely destroy the reliability of a log in the loss zone. This possibility should be avoided by careful pressure control practices.

In general, oil muds do not seriously interfere with evaluation in well-established areas. However, they eliminate the use of some logging tools such as the SP and contact resistivity tools. They also eliminate the use of show detection from samples, severely limit sidewall core and wireline test interpretation, and limit show detection from mud logging. The loss of these evaluation tools

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**Formation
Evaluation**
Continued

makes the use of oil muds in wildcats undesirable. When drilling conditions demand the use of an oil mud, more testing will often be required due to the indefinite nature of other evaluation information.

Use of high-salinity water-base muds, in general, makes logging of all kinds more difficult. It is particularly severe on SP and induction curves, which are generally our primary log. Minor electrical leakage that causes no problem in a freshwater mud can become serious in a saline mud. Abrupt changes in salinity should be avoided while penetrating untaged objective sections.

Deep filtrate invasion is also more difficult to prevent with high-salinity muds since dynamic fluid loss control is more difficult. The use of prehydrated bentonite is essentially the only effective means of control of dynamic fluid loss.

Saltwater muds have a tendency to have high yield points and gel strengths, which trap gas and mask subtle gas shows. This is true of any mud with similar rheological properties.

A clean, stable borehole is essential to logging and testing operations. This often requires adjustment of mud properties prior to these operations. If this is planned in advance, only a limited amount of time will be required to condition the hole. Stable mud properties will eliminate the need for conditioning between logging runs.

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**Formation
Evaluation**
Continued

The detection of abnormally pressured sediments during drilling operations is quite dependent on the mud. Most of the indicators used are directly affected by the mud and require that no appreciable changes in mud properties be made while they are being monitored.

A sudden increase in gel strength can cause the mud gas content to increase but will result in a measured background gas decrease if using the normal agitation trap. A significant change in chlorides in the makeup water could be falsely interpreted as an indication of abnormal pressure. Other indicators of overpressured shale (such as torque and drag, hole fill, and formation cuttings) can be affected by changing mud properties and composition.

Rate of penetration, which is regarded as the prime indicator of overpressured shale, is directly dependent on mud weight and flow properties as well as other drilling parameters. Changes in any parameter that affects rate of penetration will mask abnormal pressure indications. Consistent drilling fluid properties are needed to assure the best possible data for plotting and interpreting our indicators.

Coring is another method of formation evaluation that often requires special mud characteristics. The purpose for coring dictates the type of mud which should be used. It is impossible to obtain a core

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**Formation
Evaluation**
Continued

without an appreciable amount of flushing with filtrate. As a consequence, the measurements that are going to be made on the core dictate the type of filtrate that can be tolerated.

Water-base muds are best suited for conventional core analysis or show detection. Obviously, an oil filtrate from an oil mud will eliminate show detection, location of the oil-water contact, and oil saturation determinations. An oil mud is the best coring fluid to obtain irreducible water saturation from a core. In this case a water filtrate would introduce error in the determination. When coring is done to obtain only lithology and geologic environmental data, it doesn't matter which type of mud is used.

Sometimes cores are obtained to study wettability and water flooding characteristics. In these cases, the filtrate should contain nothing that is surface active or that will alter the wettability of the rock. Special "bland" water-base fluids that contain no chemical treating agents are used. A bentonite-in-water suspension is probably best for this application.

Formation Damage

Formation damage is related more to the type of filtrate than to the amount of filtrate lost to a formation. If the filtrate reacts with the formation solids or formation fluids, a reduction in permeability can

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Formation Damage Continued

occur. Due to radial flow geometry, only a narrow band of damage around the well bore is necessary to seriously restrict flow of fluids. If the damaged zone is sufficiently narrow that the perforations extend beyond it, no serious loss of well productivity will result. However, limiting filtrate invasion to this degree is usually not a practical means of eliminating damage to productivity.

Formation damage is often associated with water-sensitive formations. These are usually sands that contain an appreciable amount of clay solids. The degree of damage is dependent on the type of clays present in the pore space, their reactivity with the filtrate, and their mobility. Changing the salinity or ionic content of the water in the pores may cause the clay particles to either swell or to shrink and become mobile. Either effect will cause damage.

Since the type of clays and the ionic content of the connate water vary widely among different formations, there is no one best mud to prevent damage. Saturated salt water appears to minimize damage in some sands but may not be effective in others. The same is true of potassium chloride and other special-purpose types of muds. In some sands, even flushing with formation water appears to cause damage.

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Formation Damage Continued

Oil muds are often beneficial in preventing damage in water-sensitive sands. However, they do not have universal application in preventing formation damage. In some gas zones, oil filtrate may be more damaging than water. The oil-wetting ability of an oil mud filtrate may be damaging in some formations. The possibility of forming a viscous emulsion in the pore space also exists. This is especially true after subsequent cementing or acidizing operations. Unfortunately, our practices to prevent formation damage are more an art than a science. This often leads to poor choice and treatment of the drilling fluid.

Section III

RELATONSHIP OF MUD PROPERTIES TO FUNCTIONS

Relationship of Mud Properties to Functions

In order to design and maintain a mud to perform a given function, it is necessary to measure the mud properties which control its ability to perform that function. For this reason, measurements are normally made on a variety of mud properties. Considerable research has been done to design tests and to correlate these tests with the functions of a mud.

Normally, the functions of a mud are carried out downhole under conditions not easily duplicated in a mud test. Over the years, attempts have been made to either simulate more closely the downhole conditions or to predict the downhole mud properties from surface condition measurements.

Measurements of both physical and compositional properties are made in a complete mud check. Some functions are controlled directly by the mud composition, but even those which we correlate with physical properties are controlled by adjusting the mud composition. Since we normally have a multifunctional requirement for a drilling fluid, we need an extensive series of both physical and

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Relationship of Mud Properties to Functions, Continued

compositional tests in order to properly monitor a mud system. Properties should be measured on the mud going in at the suction and on the same mud coming out at the flow line.

Density

The starting point of pressure control is the control of mud density. The weight of a column of mud in the hole necessary to balance formation pressure is the reference point from which all pressure control calculations are based. The required weight of the mud column establishes the density of the mud for any specific case. Fortunately, density is one of our most accurate measurements. With a simple mud balance we are able to weigh a mud to the nearest 0.1 lb./ gal, which is equivalent to 5.2 psi per 1000 ft. of mud column. Mistakes in measuring density account for most of the inaccuracies. The most frequent mistakes are:

1. Improperly calibrated balance
2. Entrained air or gas in the mud
3. Failure in filling the balance to exact volume
4. Dirty mud balance

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Density

Continued

The calibration of a mud balance should be checked at two densities that span the range of densities to be measured. One convenient calibration check point is to measure the density of fresh water. At temperatures between 75° and 95°F, the density of water should range between 8.32 and 8.30 lb./gal. A completely suitable means of checking the calibration at the high end of the scale has not been devised. High weight muds can be used if their density is accurately known and if a representative sample can be transferred to the mud balance. Settling of solids in the sample makes it questionable whether a representative sample is used in the calibration check. Some high-density solutions have been used for this purpose, but they are highly corrosive.

If a mud balance is found to be in error by more than 0.1 lb./gal at either end of the scale, it would be advisable to obtain a new, correctly calibrated balance rather than re-calibrate or correct the readings of the old balance. The caps on mud balances should never be interchanged. A cap may weigh differently from the original and cause an error in density measurements.

When air or gas is trapped in a mud sample, it will decrease the measured density. This is especially troublesome in muds that have high yield points or gel strengths, but it can occur in any mud. There are devices which can be used to degas a mud sample. In less

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Density

Continued

severe cases the sample can be stirred on a Fann viscometer at medium speed to help "break out" the entrained gas. A pressurized mud balance can also be used to obtain correct mud densities.

It is important to fill the balance 100 percent with mud in order to obtain an accurate density. An air bubble can be trapped under the lid and cause low density measurements or granular material may hold the lid up, resulting in overfilling and a high density measurement.

The mud balance should be level and out of the wind. Air currents are often sufficient to tip the balance and affect the reading.

Density is not greatly affected by downhole conditions. Increased temperature causes the density to decrease, but increased pressure causes an increase in density. Downhole, these effects oppose one another and tend to equalize. Problems can result from large changes in measurement temperatures. If a new mud is carried to location to displace a circulating system, there may be a large difference in temperatures at which the densities of the old and new muds were measured. The cooler mud may decrease in density from 0.1 to 0.3 lb./gal when it returns to the flow line after the first circulation. To avoid this problem, the densities of both muds should be checked at the same temperature.

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Density

Continued

The density of a mud is increased by adding barite, a commercial grade of barium sulfate. Barite is used as a standard weighting agent because of its low cost, high specific gravity, inertness, and low abrasiveness. Commercial barite is a mined product that undergoes very little processing other than grinding. Its specific gravity averages about 4.25. Pure barium sulfate has a specific gravity of 4.5, indicating that some impurities are present in the commercial grade. The impurities vary depending upon the source of the barite. The color is not indicative of the purity or quality of the barite. Soluble alkaline earth metals such as calcium and magnesium are among the more detrimental types of impurities and have been limited by API specification to a maximum of 250mg/l expressed as calcium. The amount of calcium introduced into the mud system from addition of API grade barite should not be detrimental, but a calcium check on the barite should be run to assure that an abnormal amount of calcium is not present. This can occur through poor quality control at the grinding plant or from cement contamination during transporting.

Equations, charts, and tables necessary to calculate required material for weighting a mud are included in **Appendix C**.

Muds maintained at densities higher than required to control formation pressures cause a variety of problems. They decrease penetration rates, increase differential pressure sticking, increase

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Density

Continued

possibility of lost circulation, increase mud costs, and thus increase overall well cost. Consequently, density should be controlled even in unweighted muds. This amounts to solids control, which is discussed in another section.

Flow Properties

The flow (or rheological) properties of a mud are those properties which describe the flow characteristics of a mud under various flow conditions. In a mud circulating system, flow occurs at a variety of rates in conduits of different sizes and shapes. In order to know or predict the effects of this flow, we need to know the flow behavior of the mud at the various points of interest in the circulating system. To simplify the measurement procedure, we make only a limited number of measurements.

When a fluid flows, it exerts a frictional drag – called the shear stress – on the surface of the conduit. The magnitude of the shear stress depends on the frictional drag between adjacent “layers” of fluid traveling at different velocities, and the difference in velocities of adjacent layers next to the wall of the conduit. The difference in velocities between adjacent layers is called the shear rate. We are interested in the effect of the flow at the wall where both shear rate and shear stress are a maximum.

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Flow Properties

Continued

If the shear stress is known at all shear rates, the complete flow behavior of the fluid has in effect been described. For very simple fluids such as water or oil, the ratio of shear stress to shear rate is a constant. In these fluids, called Newtonian fluids, measurement of shear stress at one shear rate is sufficient to predict flow behavior at all shear rates. The ratio of shear stress to shear rate is the viscosity.

The viscosity is a single number that characterizes the flow behavior of a Newtonian fluid. When solids are added to a Newtonian fluid, the irregular shapes of these particles resist flow in a manner not directly proportional to rate of shear. The interparticle interference to flow is more pronounced at low shear rates than at higher shear rates. As a consequence, the ratio of shear stress to shear rate, or the effective viscosity, is high at low shear rates and decreases with increasing shear rate. This is known as "shear thinning." In other words, the increase in effective viscosity over that of water decreases with increasing shear rate.

The shear stress is directly proportional to the pressure required to produce the flow. In a Newtonian fluid, the smallest possible amount of pressure will cause the fluid to flow. In fluids that contain solids which link together to form a structure, flow will stop when the pressure or shear stress is reduced to a point which is less than the

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Flow Properties

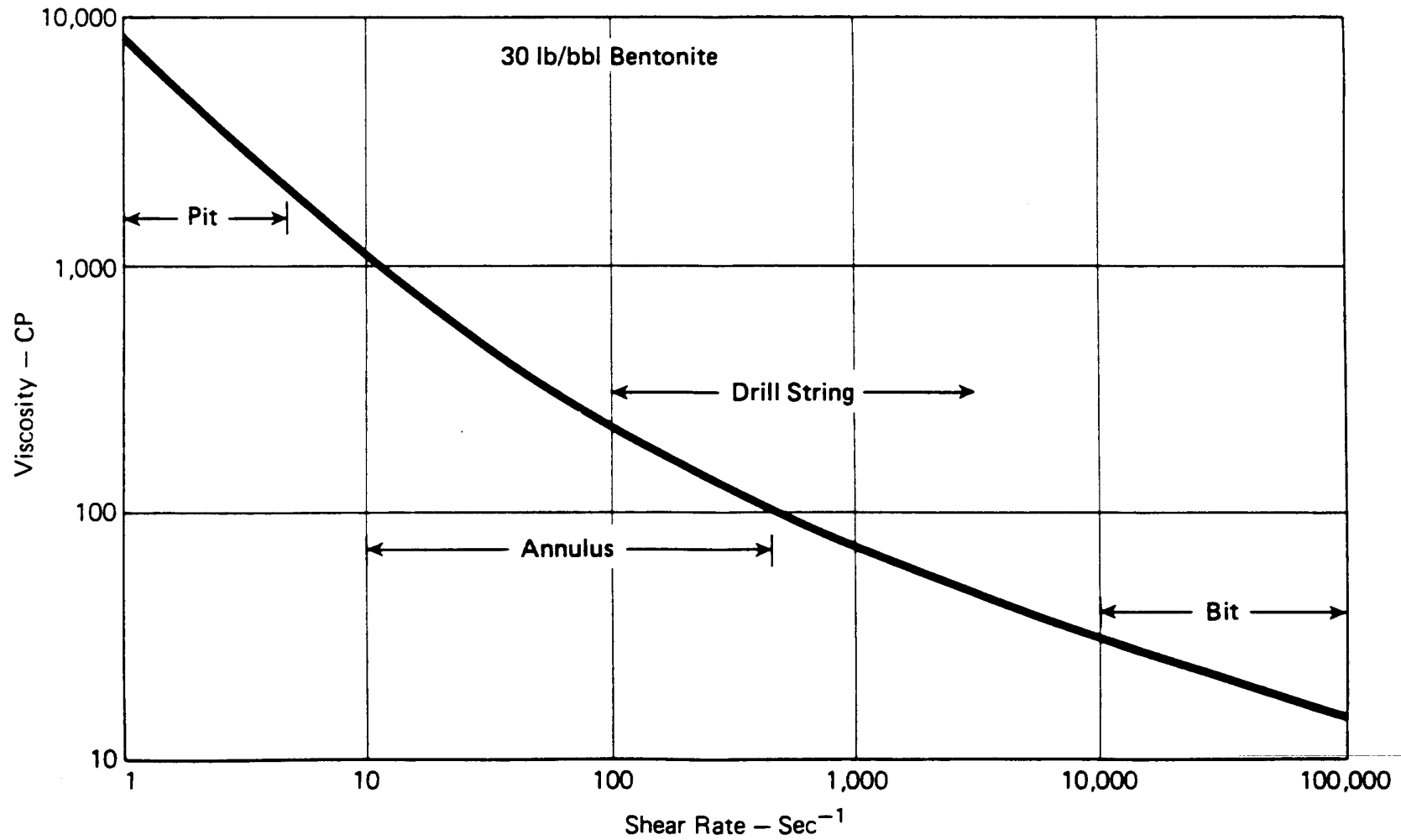
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shear strength of the structure. This point is called the yield stress of the fluid. These non-Newtonian fluids, when allowed to remain still for a period of time, continue to develop this semi-rigid structure and the shear stress required to initiate flow increases. This shear stress is called gel strength. The structure becomes more rigid with time, causing the gel strength to increase with time.

Basically, in the mud circulating system, we are interested in the flow behavior of the mud at the bit where shear rates are extremely high, in the annulus where shear rates are relatively low, and in the pits where shear rates are almost zero. We are also interested in the flow behavior inside the drill pipe and drill collars, since this controls the amount of hydraulic horsepower that a pump can deliver to the bit. **Figure I** shows the approximate shear rate ranges for the various parts of the circulating system and the effective viscosity of a bentonite suspension at these various shear rates.

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Figure 1
Viscosity Curve for Bentonite Suspension



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Flow Properties

Continued

Our basic design criteria for flow property control are to:

1. Minimize viscosity at high shear rates in order to maximize penetration rates.
2. Maintain adequate viscosity at annular shear rates to lift cuttings and sloughing and clean the hole.
3. Minimize viscosity at annular shear rates consistent with good hole cleaning when lost circulation may occur due to excessive annular pressure drop.
4. Provide adequate gel strength at all points in the system to suspend barite.
5. Prevent excessively high gel strengths from developing downhole during long periods of quiescence in order to prevent high pump pressures required to break circulation, and high swab and surge pressures.

Obviously, this list of requirements has points of conflict. A degree of compromise will always be necessary.

Several instruments are used to secure information of the flow characteristics of mud. A brief description of the various tests and interpretation of the test data follows.

Marsh Funnel

The Marsh funnel is a crude method for measuring the consistency of a fluid. Although listed on the mud check sheet as viscosity, the Funnel viscosity is not in the true sense a viscosity at all.

The test consists of filling the funnel to the bottom of the screen with mud (1500 ml) and timing how long it takes for one quart to flow out of the funnel. The time in seconds is reported as the funnel viscosity. Fresh water at 70°F will have a funnel viscosity of 26 seconds.

This test has the advantage of being quick, simple, and requiring very little equipment. It is useful in showing gross changes in the overall “viscosity” of a fluid, but it does not measure specific flow parameters. It can be changed by changes in plastic viscosity, yield point, gel strength, or density. For this reason it should be used only to monitor a mud and not to diagnose problems or to prescribe treatment.

Fann V-G Meter

The V-G meter is a rotational type viscometer in which the fluid is contained between coaxial cylinders. The outer cylinder rotates at a constant speed and the viscous drag of the fluid on the inner cylinder or bob exerts a torque that is indicated on a calibrated dial. The torque is proportional to shear stress and the rotational speed is proportional to shear rate. The indicated dial reading times 1.067 is equivalent to shear stress in lb./100 sq. ft. And the rotational speed

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Fann V-G Meter

Continued

in rpm times 1.703 is equivalent to shear rate in reciprocal seconds. Two models of the V-G meter in common use are the Fann 35 and 34. The Model 35 is a six-speed model (600, 300, 200, 100, 6, and 3 rpm) and the Model 34 is a two-speed model (600 and 300 rpm). These instruments provide measurements of the actual flow parameters of shear rate and shear stress and also provide a means of making gel strength measurements. With this information we are better equipped to diagnose flow behavior and prescribe mud treatment than with the funnel viscosity.

After the shear stress/shear rate data are collected, they can be handled and reported in a number of ways. Traditionally, these data have been used to calculate plastic viscosity and yield point in the Bingham plastic rheological model, and these parameters have been reported on the mud check sheet. The difference in the V-G Meter dial readings at 600 and 300 rpm is the plastic viscosity, and the plastic viscosity subtracted from the 300 rpm reading is the yield point (see **Figure 2**).

Since the Bingham plastic model does not truly represent the shear rate/shear stress behavior of most muds, the calculated yield point is not equivalent to the true yield stress and the plastic viscosity is not a true viscosity. However, the wealth of experience we have acquired in the use of these parameters make them quite useful in predicting mud performance and diagnosing mud problems.

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Figure 2
Bingham Plastic Model

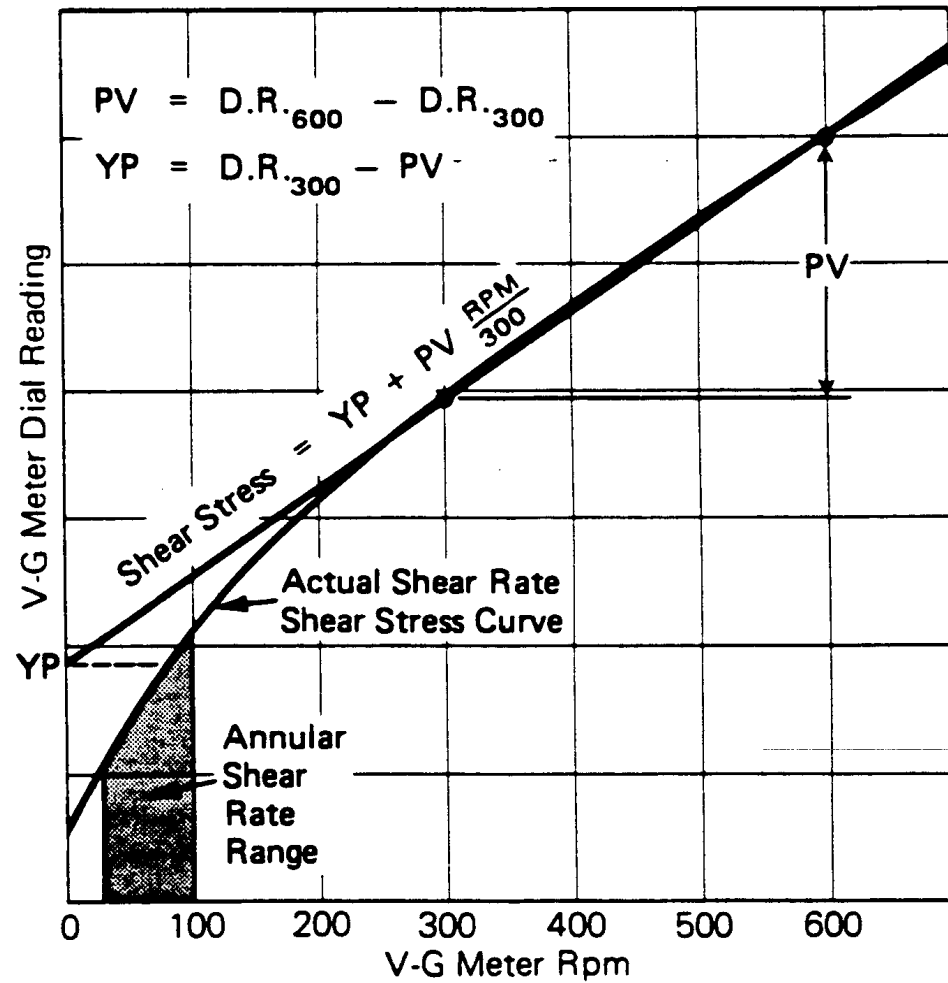
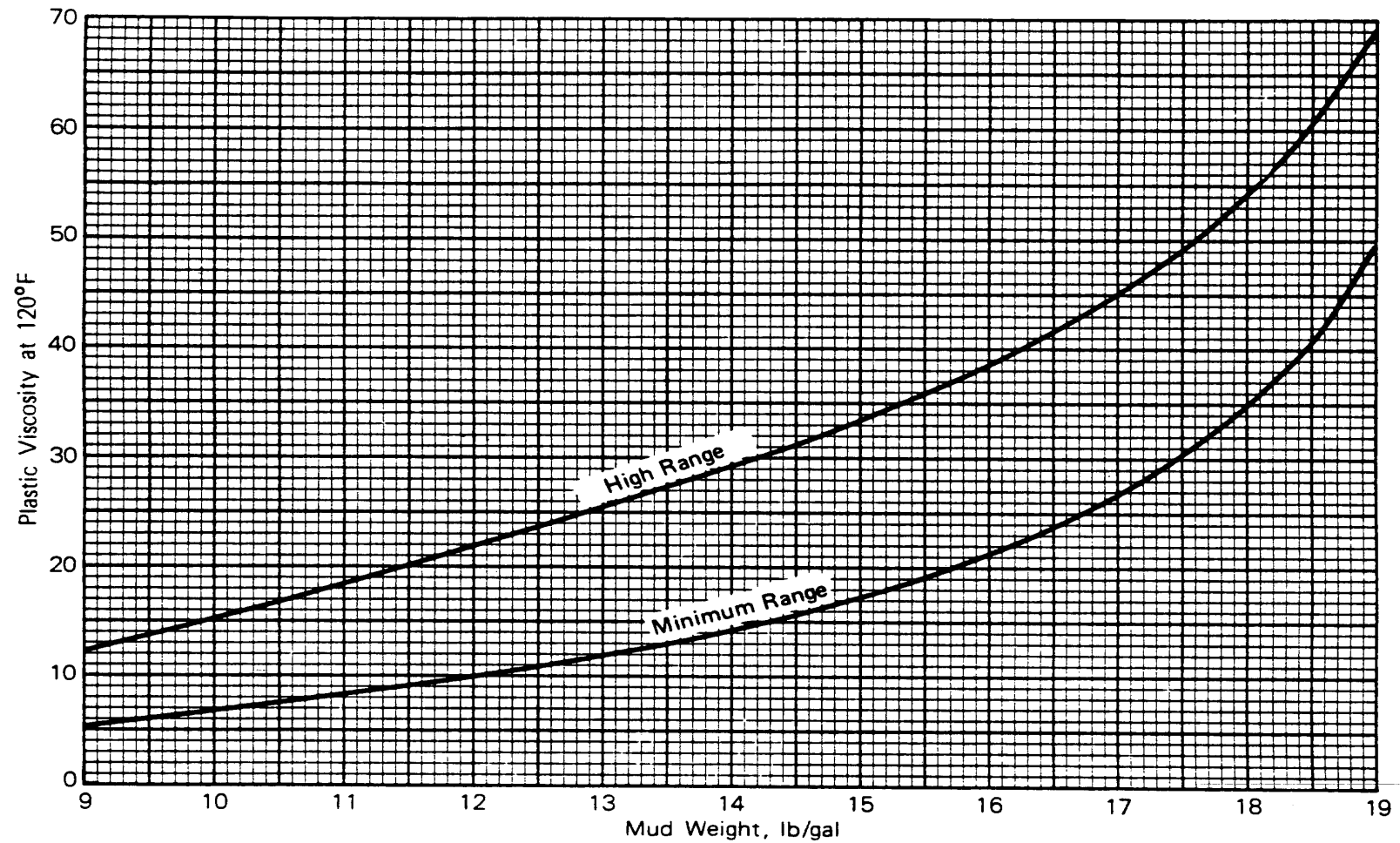


Figure 3
Suggested Range of Plastic Viscosity



Plastic Viscosity

Although calculated from measurements at relatively low shear rates, the plastic viscosity is an indicator of high shear rate viscosities. Consequently, it tells us something about the expected behavior of the mud at the bit. One of our design criteria was to minimize the high shear rate viscosity. To accomplish this, we should minimize the plastic viscosity. A decrease in plastic viscosity should signal a corresponding decrease in the viscosity at the bit, resulting in higher penetration rate.

Increasing the plastic viscosity is not a desirable means of increasing the hole-cleaning ability of a mud. In fact, the increase in pressure drop down the drill string, caused by an increase in PV, would reduce the available flow rate and tend to offset any increase in lifting ability. In general, high plastic viscosity is never desirable and should be maintained as low as practical.

The plastic viscosity is primarily a function of the viscosity of the liquid phase and the volume of solids contained in a mud. The viscosity of the liquid phase is increased by addition of any soluble material. Many of the water-soluble polymers used for fluid-loss control are quite effective in increasing the plastic viscosity. Saturated salt water has twice the viscosity of fresh water. Diesel oil, which is commonly used as the liquid phase of oil-base muds, has three times the viscosity of fresh water. Both salt water muds and oil muds tend to have high plastic viscosities.

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Plastic Viscosity

Continued

The volume of solids in a mud, is the dry volume of solids plus the increase in volume due to hydration. The water of hydration actually becomes a part of the solid so far as its effect on viscosity is concerned. In other words, the plastic viscosity is increased by addition of any type of solid; but solids such as clays, which hydrate, will further increase the plastic viscosity as their volume is increased by hydration. This makes the hydration and dispersion of shale particles particularly detrimental. As long as these particles are large and relatively unhydrated, their effect on viscosity is small. However, time, temperature, and agitation tend to disperse and allow hydration of the individual clay platelets, which results in increased viscosities.

In order to combat the tendency of shale particles to disperse and hydrate, the "inhibitive" muds were designed. Materials such as lime, gypsum, lignosulfonate, and polymers are added to inhibit the rate of dispersion and hydration. These materials do cause inhibition, but if the inhibited particles are not removed from the system, the solids content will continue to build. In time, the plastic viscosity will be as high or higher than before and other mud properties such as filter cake thickness will suffer.

Minimum plastic viscosities can be achieved only to the degree that the mud is kept free of drilled solids. **Figure 3** shows guidelines for plastic viscosity of water-base muds at various mud weights. The

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Plastic Viscosity

Continued

lower curve represents muds that contain only barite and sufficient bentonite to suspend the barite. This curve should represent minimum plastic viscosities for good mud performance. The upper curve is an average for many field muds that have been checked. Note that these curves are based on measurements at 120°F. Plastic viscosity decreases with increasing temperature, due to thinning of water. If the mud is checked at 130°F, the PV will be about 10 percent lower than at 120°F; if it is checked at 110°F, it will be about 10 percent higher. For this reason, all mud tests should be made at the same temperature, 120°F.

Yield Point

The yield point, calculated from the Bingham equation, is not the true yield stress necessary to maintain flow, but is a value which is somewhat higher. In fact, it is normally close to the value of the shear stress at annular shear rates. Anything that causes changes in the low shear rate viscosities will be reflected in the yield point. For this reason, it is a good indicator of flow behavior in the annulus and compositional changes that affect the flow behavior in the annulus.

When a fluid contains large molecules (such as a polymer solution) or colloidal particles, these molecules or particles tend to "bump" into one another, increasing the resistance to flow. If these particles are quite long compared to their thickness, the interparticle

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Yield Point

Continued

interference will be quite large when they are randomly oriented in the flow stream at low shear rates. However, as the shear rate is increased, the particles will "line up" in the flow stream and the effect of particle interaction decreases. If particles are electrically attracted to one another, the effect is quite similar. At low shear rates the particles link together, increasing the resistance to flow; at high shear rates the linking bonds are broken and the fluid becomes more like water.

These two effects combine to determine the yield point of a mud. The electrical interaction of solids is controlled by chemical treatment, and the mechanical interaction is controlled by adjusting the type and amount of solids or polymer in a mud.

Clay platelets are both electrically charged and long compared to their thickness. This makes them quite good for increasing the yield point. Their ability to link together (flocculate) can be neutralized by the addition of certain chemicals such as tannins, phosphates, and lignosulfonates. When this is accomplished, the yield point will be reduced to that caused by the mechanical interactions of the solids. Further chemical addition will not continue to reduce the yield point past this point. Complete deflocculation is best identified by the occurrence of near zero gel strength. Removal of colloidal solids is

Continued on next page

Yield Point

Continued

another way to reduce the yield point. This reduces both the tendency to link and the mechanical interference of the particles.

When a higher yield point is desired, addition of bentonite is a cheap and effective means. It is most effective when well hydrated and dispersed in fresh water. This insures a maximum amount of charged surface area exposed per volume of bentonite added. The presence of deflocculating chemicals, of course, defeat your purpose by neutralizing the ability of the platelets to link together. In some cases, flocculating agents or clay “extenders” are added to promote linking and cause even higher yield points to result. Such materials as soda ash, polyacrylates, and several different calcium compounds are used for this purpose.

In summary, high yield points are caused by flocculation of clay solids or high concentrations of colloidal solids. Flocculation may be due to lack of sufficient deflocculent, high temperature, or contaminants such as salt, calcium, carbonates, and bicarbonate. A high solids concentration will aggravate flocculation tendencies from any cause.

The yield point is primarily associated with two mud functions: the hole cleaning capability and the pressure control characteristic of a mud. A higher yield point increases the carrying capacity of a mud and increases the circulating pressure drop in the annulus.

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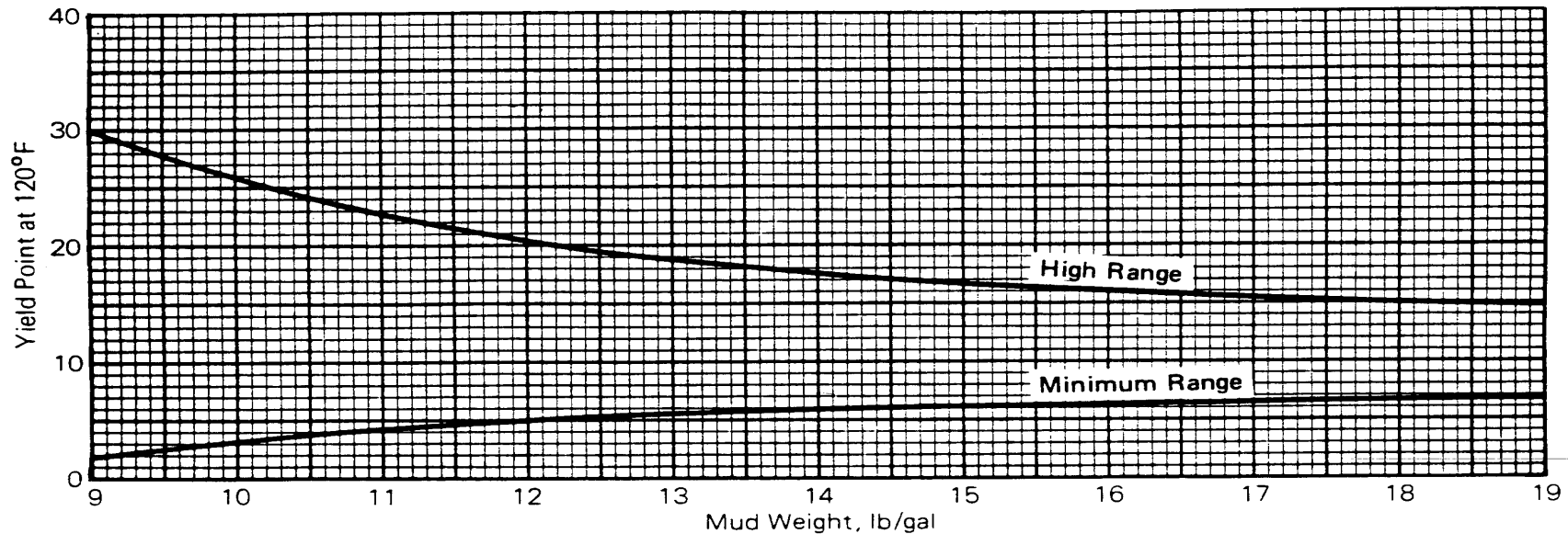
Yield Point Continued

Associated with increased circulating pressure drop is increased pressure surge and swab from pipe movement. Since an increased yield point aids hole cleaning but is detrimental to the problems of lost circulation and swabbing, a compromise must be reached. For this reason, no absolute guide line for yield point values can be given.

High mud weights improve hole cleaning capabilities of a mud. Consequently, high yield points are normally not necessary in high-weight muds to insure good cutting carrying capacity. Also, pressure control is often critical where high-weight muds are required. As a result, the need to minimize yield point usually outweighs any advantages of maintaining a high yield point in high density muds. A yield point range for various weight muds is shown in **Figure 4**.

Continued on next page

Figure 4
Suggested Range of Yield Point



Gel Strength

The gel strength is a measurement of the shear stress necessary to initiate flow of a fluid that has been quiescent for a period of time. It is caused by electrically charged particles that link together to form a rigid structure in the fluid. The strength of the structure formed is a function of the amount and type of solids in suspension, time, temperature and chemical environment. In other words, anything which promotes or prevents the linking of particles will increase or decrease the gelation tendency of a mud.

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Gel Strength

Continued

Gel strength is measured by beginning to turn the V-G meter at a very low speed and reading the peak dial deflection. This represents the shear stress necessary to break the gel structure and is recorded as gel strength in lb/100 sq. ft. The gel strengths recorded on the mud check sheet are measured after set times of 10 seconds and 10 minutes. These set times are arbitrary and have been selected simply to provide a standard basis of comparison of gel building characteristics of muds. The difference in the two measurements is an indication of the rate of gelation.

It is necessary for a weighted mud to have gel strength of about 2 to 4 lb/100 sq. Ft in order to suspend barite. The barite will settle in a mud that has no gel strength. Regardless of its viscosity. A high viscosity will simply slow the rate of settling. In a water-base mud that contains clay solids, the development of gel strength is a natural thing. Barite settling should never be a problem unless these clay solids have been made inert by excessive chemical treatment. In such cases, addition of prehydrated bentonite should solve the problem. Barite suspension in oil muds is somewhat more difficult since clay solids are essentially inert in oil. Even the oil-wet clays used in some oil muds to build viscosity are not particularly good at building barite-suspending ability. It should be emphasized again that a high viscosity is not sufficient to suspend barite. A gel strength of 2 to 4 lb/100 sq. ft is necessary.

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Gel Strength

Continued

In water-base muds, flocculation increases gel strength and deflocculation decreases gel strength. An increase in gel strength is normally the first indication of the beginning of flocculation. In fact, the 10 minute gel strength will usually begin to increase before the initial gel strength. If a pilot test with additional lignosulfonate fails to reduce the gel strength, it signals either an excessively high colloidal solids content or a chemical contamination problem. Dilution with water will temporarily solve either problem, but in a most expensive manner. Water chemistry test should be run on the mud filtrate to determine what contaminants are present. A check of the alkalinities may indicate that there is insufficient hydroxyl ion content to activate the lignosulfonate or that an excessive concentration of carbonate or bicarbonate is causing flocculation. When problems involving improper water chemistry are present, the mud treating costs usually increase drastically due to dilution which is necessary to control the flow properties.

Solids Analysis

The primary source of control of rheological and filtration properties of a mud is the amount and type of solids in the fluid. To properly control solids, it is necessary that we know the amount of each of the various types of solids in a mud. A good estimate of the amounts of the various types of solids can be made from tests that are normally performed on a mud.

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Solids Analysis

Continued

If we assume that all the suspended solids in a mud have a specific gravity of either 4.25 (barite) or 2.6 (drilled solids and bentonite), we can make measurements that will allow calculation of the relative amounts of these two types of solids. We need to know the volume percent water and its specific gravity, the volume percent oil and its specific gravity, the volume percent solids, and the mud density.

With the mud retort we can measure the volume percent oil and the volume percent distilled water in the mud. When there is a large amount of dissolved salts in the mud, the volume percent distilled water from the retort is less than the actual volume percent salt water in the mud. These dissolved salts increase the volume of water as well as its specific gravity. If the salt in the mud is predominantly sodium chloride, we can measure the chloride content of the filtrate and calculate the specific gravity and corrected water volume. Knowing the actual water volume and oil volume, the suspended solids can be calculated by difference. Using the mud density and the volume percent suspended solid, the relative amounts of barite and low-gravity solids can be calculated.

Knowing the volume percent low-gravity solids is important, but it is also desirable to know the relative amounts of high-yield bentonite and low-quality drilled solids that comprise the low gravity fraction. Since different types of solids have different cation exchange

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Solids Analysis

Continued

capacities, it is possible to differentiate between bentonite and the low-quality drilled solids, which have much lower exchange capacities. If we know the volume percent low-gravity solids and the cation exchange capacity (methylene blue test), we can estimate the percent bentonite and the percent drilled solids.

A detailed description of calculation procedures for analyzing solids composition of a mud is given in **Appendix B**.

Retort

A retort or mud still is a device used for measuring the liquid content of a mud. A measured sample of mud is heated until all the liquid components (both water and oil) have been vaporized. The vapors are cooled through a condenser and the liquids are collected in a graduated cylinder. The most common retorts use either 10 or 20 cc of mud. The 100 percent line on the graduated cylinder should be exactly the same volume as the mud sample. If the mud cup and the graduated cylinder are not exactly the same volume, an error in measurement will result. Corrosion can cause metal loss inside the mud cup, resulting in an increased volume, or the graduated cylinder may be incorrectly calibrated. If the mud cup volume is greater than the graduated cylinder, the calculated solids volume will be less than actual and, conversely, the solids will read too high if the cylinder is larger than the cup. When preparing the sample for testing, the mud

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Retort Continued

The volume percents oil and water as read from the graduated cylinder are recorded on the mud check sheet. The sum of these two numbers subtracted from 100 is recorded as volume percent solids. If the mud contains as much as 20,000 mg/l chlorides, the total solids number should be corrected (see **App. B**).

In muds which contain no barite, the total solids can be calculated from mud density. This is probably more accurate than a retort analysis. A chart for making this determination is given in **Appendix B**.

Correlation of mud solids composition with flow properties is important to proper interpretation of the flow properties. For instance, a high plastic viscosity is an indicator of high solids content, but it should be confirmed by solids analysis. The high plastic viscosity could be caused by a high viscosity of the base liquid due to high polymer or bentonite content. A high yield point often indicates a high concentration of low-gravity solids, but it may be caused by a chemical imbalance in the mud. A solids analysis and a filtrate analysis may both be necessary to diagnose a yield point problem.

The solids composition should also be correlated with filtration properties for similar reasons. Adequate bentonite content is critical for good filtration control, and the drilled solids content should be a minimum to minimize cake thickness and insure good cake quality.

Methylene Blue Test

The methylene blue test is a method for measuring the cation-exchange capacity of clay solids. The cation-exchange capacity of a clay mineral is a measure of the ability of the clay to carry exchangeable cations. Since it is through hydration of the exchangeable cations that clay derives its swelling ability, the cation-exchange capacity is a rough indicator of the rheological and filtration characteristics of a clay suspension.

When the methylene blue test (MBT) is run on a mud, the total cation-exchange capacity of all the clays minerals present in the mud is measured. Since clay minerals other than bentonite also have exchange capacity, the test is not a direct measurement of the bentonite content. It is normal procedure, however, to report the MBT as the amount of Wyoming bentonite that it would take to obtain the same methylene blue capacity.

An estimate of the actual amount of bentonite in a mud can be obtained if we know the relative exchange capacities of bentonite and the drilled solids. It has been found that on an average, the drilled solids will have about one ninth the exchange capacity of bentonite. Using this ratio of nine to one on exchange capacities, the clay solids fraction calculated from the retort analysis can be subdivided into bentonite and drilled solids. This procedure is quite helpful in determining the “quality” of the colloidal fraction of a mud.

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**Methylene Blue
Test**
Continued

It should be noted that the cation exchange capacity is a measurement of a clay property. How that clay will perform in a suspension depends on the chemical content of the water. For this reason, we cannot assign ideal MBT values for various mud weights without specifying the water chemistry.

As salinity of the water is increased, it takes an increased amount of bentonite to build the same viscosity. For good mud properties, it takes roughly twice as much bentonite in sea water as it does in fresh water. In other words, the MBT values of seawater muds are going to run about twice as high as for equivalent fresh water muds.

Since the MBT is a measurement of the "active" solids in a mud, it should correlate with the yield point and gel strength of the mud. High yield point and gel strength values can be caused by either a high concentration of active solids or by flocculation due to temperature or contaminants. If the MBT values do not increase during a period of time when the yield point has increased, the problem must be due to chemical causes. Conversely, if the MBT values have been on an increasing trend with the yield point, an excessively high clay content is indicated. Correlation of physical properties with composition is often necessary in order to properly prescribe treatment.

Filtration

Filtration occurs any time a permeable formation is exposed to a mud at a pressure higher than the formation pressure. The pressure causes filtrate to flow into the rock and deposit mud solids on the walls of the borehole. Thus, filtration causes two distinctly different types of problems-those due to filtrate invasion and those due to filter cake deposition.

The problems caused by filtrate invasion are not drilling problems, but are formation evaluation and completion problems. Excessive fluid loss may cause flushing of the zone around a wellbore to the extent that logging and formation test information is incorrect. This is normally not a problem with weighted muds where filtration control is necessary for control of filter cake deposition. In clear water or low solids muds, excessive flushing may present problems.

Another problem is invasion of a formation by a liquid that will greatly reduce the formation permeability. Most of the resistance to flow occurs close to the wellbore due to the radial geometry.

Consequently, the volume of filtrate lost is not as important as the type of filtrate. When a mud with nondamaging filtrate is used to drill a well, equal care should be taken on subsequent operations such as cementing or acidizing to prevent damage from these liquids.

From the standpoint of the drilling operation, the filter cake is of more concern than the volume of filtrate. The filter cake has a direct

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Filtration

Continued

bearing on such problems as differential pressure sticking, torque and drag, lost circulation, and poor primary cement jobs. Our basic aim is to minimize the thickness and permeability of the deposited cake.

There are two types of filtration: dynamic and static. Dynamic filtration occurs when the fluid is being circulated and static filtration occurs when the fluid is at rest. Dynamic filtration differs from static filtration in that the flow of mud tends to erode away the cake as it is deposited by the filtration process. The filter cake builds until the rate of deposition equals the rate of erosion. When it reaches an equilibrium thickness, the rate of filtration becomes constant. This is in contrast to static filtration where the cake continues to grow thicker with time, causing the rate of filtration to continually decrease. After equivalent filtration times, a static cake will be thicker than a dynamic cake and the static rate of filtration will be less than the dynamic rate. Consequently, we should control static filtration in order to control filter cake thickness and dynamic filtration should be controlled in order to control filtrate invasion.

Dynamic Filtration

When filtration begins on a freshly exposed rock surface, the flow of filtrate into the rock is relatively great. Solids carried by the filtrate are deposited as a filter cake. As the cake grows thicker, the rate of filtrate flow decreases and the rate of solids deposition also decreases. If the mud is circulated at a steady rate, a point will be reached at which the flowing mud will carry away the solids as fast as they are being carried to the cake surface by the flow of filtrate into the cake. At this time the cake thickness and the filtration rate become constant. This equilibrium condition is normally reached within an hour.

If either the erosion rate or the deposition rate is changed, a new equilibrium cake thickness and filtration rate will be established. A decrease in erosion rate will cause an increase in cake thickness and a decrease in filtration rate. An increase in deposition rate will also cause an increase in cake thickness and a decrease in filtration rate.

The erosion rate is a function of annular velocity, mud viscosity, and flow regime. An increase in annular velocity or mud viscosity will cause an increase in erosion rate, resulting in an increased filtration rate. Changing from laminar to turbulent flow will also increase the erosion rate. In laminar flow, doubling the velocity will cause the filtration rate to be doubled. In turbulent flow, doubling the velocity

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Dynamic Filtration Continued

will cause the filtration rate to be increased by a factor of four. As a consequence, insuring that the flow regime is laminar in the annulus and that the velocity is as low as practical will insure greatly reduced dynamic filtration rates

The viscosity of the mud is important. An increase in viscosity will cause a proportionate increase in erosion rate. Fluid-loss control agents that cause large increases in mud viscosity may actually cause the dynamic filtration rate to be increased.

The deposition rate is controlled by the rate at which solids are carried to the cake by the flow of filtrate. When the solids content of a mud is increased, the same volume of filtrate will carry more solids to the cake. This will cause an increased deposition rate and will result in a thicker equilibrium cake and reduced filtration rate. If these solids are the type that form low permeability filter cakes, a small increase in equilibrium cake thickness will cause a significant decrease in filtration rate. Bentonite appears to be the most effective additive in reducing dynamic filtration rate. Sizable decreases in filtration rate can be obtained with increasing bentonite concentrations up to about 25 lb./bbl. At higher concentrations the bentonite causes very rapid increases in mud viscosity, resulting in increased erosion rates and minimizing further reductions in filtration rate.

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Dynamic Filtration

Continued

Materials such as lignosulfonate, lignite, oil, starch, and CMC, which are used to reduce static filtration, have little effect on dynamic filtration. These materials reduce the cake permeability, causing a decrease in the equilibrium cake thickness rather than a reduction in filtration rate. As a result, reducing the static API fluid loss with these materials will not cause a corresponding reduction in the dynamic filtration rate.

Static Filtration

Static filtration control is necessary in order to control the characteristics of the filter cake deposited downhole. It is the cake which is the source of filtration-related drilling problems. We are interested in the thickness of the cake, its permeability, slickness, and texture. Filtrate volume is only one of the indicators that can be used to evaluate filtration characteristics of a mud. Therefore we should concern ourselves with all the cake characteristics rather than only with the filtrate volume.

It is always desirable that the filter cake be thin. This is the most important requirement placed on the filtration characteristics of a mud. The next characteristic in importance is that the cake has a low permeability. This, too, is always desirable and usually goes hand-in-hand with a thin cake. Although these characteristics are related to a low fluid loss, other factors can also cause a low fluid

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Static Filtration Continued

loss. A high solids content can cause the fluid loss to be low but result in a thick cake. Depending on the quality of these solids, the cake permeability may also be high. This is obviously not a desirable situation but one that can occur if we place too much emphasis on fluid loss alone.

The permeability of the cake is proportional to the product of fluid loss and cake thickness. If both fluid loss and cake thickness are low, the permeability will be low and our basic requirements will be met.

It is difficult to measure the cake thickness with a high degree of accuracy. The basic problem is in determining where the gelled mud ends and the filter cake begins. This is especially true in unweighted or low-density muds. High-density muds form filter cakes of higher solids content, so the boundary between mud and cake is more easily distinguished. A standard method for measuring cake thickness should be adopted and this measurement made and recorded on all filtration tests with the greatest accuracy that can be accomplished. This measurement is actually more important than the filtrate volume since it correlates directly with drilling problems.

When we have attained our initial goals of minimum fluid loss and minimum cake thickness, we have basically solved the filtration problems for most situations. Further refinements in the cake

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Static Filtration

Continued

The slickness of a cake is related to the frictional drag that can develop during differential pressure sticking. A relative measurement of this property can be obtained with the “stickometer”. The absolute numbers generated with this test are only rough indicators of the ability of the mud to alleviate sticking, but subsequent tests are useful in establishing trends. The effect of a mud treatment on this property can be evaluated with the test. It is normal for the sticking coefficient measured with this instrument to increase with increasing mud density due to the increased solids content of the cake. This increase can be minimized by removal of drilled solids and addition of bentonite or special lubricating additives. The stickometer test is particularly useful in evaluating the effects of special additives used to prevent sticking.

The texture of a filter cake is a characteristic for which no direct test is run. It is so closely related to the other cake characteristics that it will probably never be a problem if the other cake properties are in good shape. For instance, a fluffy filter cake will probably also have a high permeability and be excessively thick. A dry, brittle cake has a high solids content and will have a high sticking coefficient.

When all of the cake characteristics are taken into account, a much better picture of the filtration characteristics of a mud will be obtained. Specific mud problems can be spotted that otherwise could go undetected while treating the wrong problem.

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Static Filtration Continued

Two static filtration tests are normally run—a low-temperature test run at surface temperature and 100 psi filtration pressure, and a high-temperature test run at 300°F and 500 psi filtration pressure. These two tests span the range of temperatures from surface to bottom for most wells drilled. They also serve as reference tests so that changes in the mud can be detected and the filtration properties of a mud can be correlated with other jobs where the same tests were run.

The low-temperature test is quicker and more easily performed than the high-temperature test. For this reason, it is normally run more frequently to detect any sudden changes in the filtration behavior of a mud. It should not be used exclusively when the bottom-hole temperature exceeds 180°F or when there is any reason to believe that the temperature downhole may detrimentally affect the mud.

The 300°F test is used to evaluate filtration behavior when the downhole temperatures get high enough to significantly affect the filtration behavior. This can occur from temperature induced flocculation, degradation of a fluid-loss control additive, or any unpredictable temperature reaction. Even though the 300°F test usually does not duplicate the downhole temperature, it is an indicator of whether a mud is stable up to a temperature of 300°F. If the bottom-hole temperature exceeds 300°F, a filtration test should

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Static Filtration Continued

also be run at this temperature. When the expected maximum bottom-hole temperature is considerably less than 300°F, a fluid-loss test should be run at this temperature. Treating a mud to have good fluid-loss control at temperatures higher than necessary is expensive.

When the temperature of a mud is increased, the fluid loss will increase due to reduction in viscosity of the filtrate. If a mud is otherwise thermally stable, the fluid loss will increase in the same proportion as the decrease of the square root of a filtrate viscosity. When a mud is heated from 75°F to 250°F, the viscosity of the filtrate is decreased by a factor of four, resulting in the fluid loss increasing by a factor of two. **Figure 5** shows the effect of temperature on fluid loss. Fluid-loss tests can be run on a mud at two different temperatures, but at the same filtration pressure, and the ratio of the two values compared with the ratio of the relative values from this curve. If the test value indicates a greater change with temperature than predicted from the curve, the mud is probably thermally unstable. This is one of the best tests for thermal stability. Unfortunately, the low-temperature and high-temperature API tests cannot be compared in this manner since they are run at different pressures. Pressure also has an effect on fluid loss, depending on compressibility of the filter cake. Normally, the 300°F-500 psi fluid

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Static Filtration

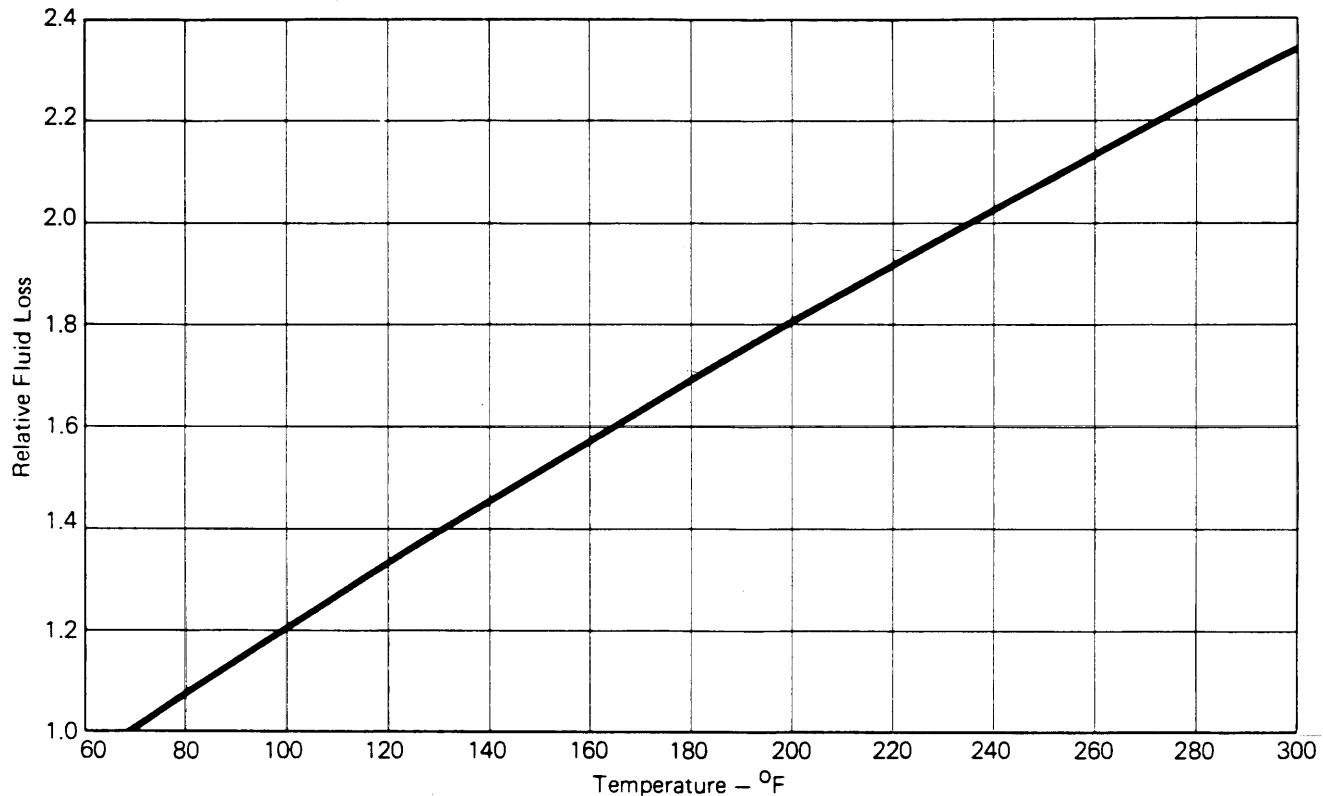
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loss will be 2 to 4 times greater than the low temperature-100 psi fluid loss. If the factor is greater than four, temperature-induced flocculation or breakdown of one of the mud components is probable. If the factor is less than two, a mistake in measurement is indicated. It could mean that the filtrate volume in the high-temperature test was not multiplied by two before reporting. This is necessary since the filtration area of the HTHP cell is half that of the low-temperature cell.

The temperature at which the low-temperature test is performed, also makes a difference. For water-base mud in the temperature range of 70°F to 140°F, the fluid loss will increase about 10 percent for each 15° increase in temperature. An effort should be made to run all tests at approximately the same temperature.

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Figure 5
Effect of Temperature on Fluid Loss Due to Change in Filtrate Viscosity



Static Filtration Continued

Additional information, which is useful in diagnosing filtration problems, can be derived from filtration tests at different pressures and the same temperature. The effect of pressure on fluid loss is largely controlled by the colloidal solids content

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Static Filtration

Continued

of the mud. If the solids in the filter cake are deformable under pressure, such as hydrated clay particles, increased pressure will cause a decrease in cake permeability, which in turn minimizes any increase in fluid loss. If the solids are rigid, such as sand and silt particles, the permeability will not reduce under pressure and the entire effect of pressure will be reflected in the fluid loss. The theoretical maximum for this effect is for the fluid loss to increase as the square root of filtration pressure. The maximum effect of filtration pressure between 100 and 500 psi would be a factor of 2.24. For a fresh water bentonite suspension, the 500-psi fluid loss will be only about 10 percent higher than the 100 psi fluid loss, due to the compressible nature of the filter cake and the resulting reduction in permeability. These two cases represent the extremes that will normally be obtained with a drilling mud. From this the quality of the colloidal solid content of a mud can be judged. There is one exception that should be noted. If a mud is flocculated, sometimes the 500-psi fluid loss will be lower than the 100-psi fluid loss. This is a result of the higher pressure crushing the flocs, causing a rather dramatic reduction in cake permeability. This condition normally occurs only in a low-density, flocculated mud. It should be pointed out that this discussion has been concerned with the filtration, or differential pressure and not the absolute, or hydrostatic downhole pressure. The absolute pressure affects fluid loss only through its effect on the filtrate viscosity. This is a very

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Static Filtration

Continued

small effect on water, but it is quite substantial in an oil mud. An increase in pressure from atmospheric to 10,000 psi will cause an oil mud filtrate to double in viscosity. This will cause the fluid loss to be reduced by 30 percent.

Water Chemistry

A knowledge of the water chemistry of a mud is essential in diagnosing and treating a mud problem. A mud is basically a solids dispersion in water with organic and inorganic chemical compounds added to impart specific properties to the suspension. Clay solids are dominant in their influence on the physical properties of a mud, and the chemical environment to which they are exposed is critical to their performance.

Other than the indirect influence on the physical properties of a mud, water chemistry is also important to corrosion control, effects on formation evaluation and formation damage, and detection of salt water influx.

The water chemistry tests normally made are:

1. pH and alkalinity
2. Total hardness, or calcium and magnesium
3. Chlorides

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Water Chemistry

Continued

Several other tests are run in special situations. A potassium ion determination may be run when using a potassium-based drilling fluid. A check for soluble sulfides is used when hydrogen sulfide is present, and a number of tests are run to determine concentrations of specific mud additives.

Most of these tests are run on the mud filtrate. This filtrate should come from the low-temperature filtration test. The HTHP filtrate is often chemically altered and will give erroneous results.

pH and Alkalinity

The pH of a solution is a measure of its hydrogen ion concentration. At each hydrogen ion (H^+) concentration, there is an equilibrium concentration of hydroxyl (OH^-) ions. By measuring the hydrogen ion concentration, we are, in effect, also measuring the hydroxyl ion concentration. In pure water, the H^+ and OH^- concentrations are the same. This is the neutral point, or a pH of 7. When acid is added to water, the pH decreases on a scale from 7 to 0. When a base (caustic) is added to water, the pH increases on a scale from 7 to 14. The pH scale is logarithmic. This means the hydrogen or hydroxyl ion concentration changes by a factor of ten for each unit change in pH. In other words, a solution at pH 10 has 10 times the hydroxyl ion concentration of a solution at pH 9.

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pH and Alkalinity

Continued

The additional hydroxyl ions required to raise the pH of water from 7 to 9.5 is the same as is required to raise the pH from 9.5 to 9.8.

This shows that the reserve of hydroxyl ions is very small below a pH of 9.5. The reserve is subject to rapid change if anything that will react with hydroxyl ions, such as acid gas or clay solids, is introduced into the mud.

Maintaining an adequate pH in a mud is important for a number of reasons.

1. Corrosion rates are suppressed at a pH above 10.
2. Hydroxyl ions neutralize the H^+ ions from H_2S and prevent hydrogen embrittlement. A pH above 11 should be maintained if H_2S is anticipated.
3. Organic additives such as lignite and lignosulfonate require a pH above 9.5 in order to function effectively.
4. The rate of thermal degradation of lignosulfonate is reduced at a pH above 10.
5. Magnesium is precipitated from sea water at pH 10.
6. Calcium solubility is reduced as pH is increased.

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pH and Alkalinity

Continued

When all of these factors are taken into consideration, there are few, if any, occasions when the mud should be maintained at a pH below 9.5. Usually, the mud pH should be kept in the range between 10 and 11.5. A pH above 11.5 should be avoided unless a lime mud is being used. An ultra-high pH is detrimental to most organic additives and can cause flocculation of the clay solids. This is basically the problem encountered in cement contamination. The high yield point, gel strength, and fluid loss that occur are largely due to the sudden increase in pH to very high levels, rather than to the small amount of calcium introduced into the system.

There are two basic ways of measuring pH: either a pH meter or pH paper test strips. A pH meter is preferred. The pH paper does not have the inherent accuracy of a meter and becomes unreliable in the presence of high salt concentration or dark filtrate. A sodium-compensated electrode should be used on the meter when measuring pH of high salt content solutions.

The alkalinity of a solution is related to pH in much the same manner as heat capacity is related to temperature. Alkalinity is the combining power of a base with an acid. It is a measure of the amount of acid required to reduce the pH of a solution to a specified value. Different solutions require different amounts of acid to reduce the pH just as different substances require different amounts of heat

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pH and Alkalinity

Continued

removal to reduce the temperature. This is due to the presence of buffering ions and substances that react with the acid in addition to the hydroxyl ions in solution.

Two filtrate alkalinities are normally measured, the P_f and M_f . The P_f alkalinity is the number of cubic centimeters of 0.02 normal sulfuric acid necessary to reduce the pH of 1 cc of filtrate to 8.3, which is the color change end point of phenolphthalein indicator solution. The M_f , or total alkalinity, is a measure of the amount of the same acid necessary to reduce the pH of the filtrate to 4.3, which is the color change end point of methyl orange indicator solution.

The significance of titrating to these specific values of pH is due to the presence of carbonate ($\text{CO}_3^{=}$) and bicarbonate (HCO_3^-) ions in many mud filtrates. The carbonate ion reacts with acid to form bicarbonate. This reaction is completed when the pH is reduced to 8.3. Also at this pH, essentially all of the hydroxyl ions have been neutralized. As a result, P_f alkalinity is a measure of the combined contributions of hydroxyl and carbonate alkalinities. As the pH is further reduced to 4.3, the acid reacts with bicarbonate ions to convert them to CO_2 and water. From these two alkalinity determinations, it is possible to calculate the amounts of hydroxyl, carbonate, and bicarbonate ion in solution if no other interfering ions are present. Unfortunately, in many mud filtrates, organic acid and

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pH and Alkalinity

Continued

buffering ion such as chromate are present and contribute to the measured M_f alkalinity. There are other, more detailed, titration procedures that can be used to circumvent this problem (see **Appendix D**).

High concentrations of carbonate or bicarbonate ions in a mud cause high gel strength to develop, which cannot be reduced by addition of thinners. This leads to dilution of the mud system with water in order to control the flow properties and excessively high mud costs result. The alkalinities should be watched carefully in order to avoid this problem. The beginning of the problem is indicated when the M_f begins an increasing trend and the pH decreases or requires a larger than normal amount of caustic to hold constant. If this happens in conjunction, with an increasing trend in the 10-minute gel strength which normal treatment with lignosulfonate will not control, it is time to begin slow additions of a soluble form of calcium, such as gypsum or lime. The calcium will combine with carbonate to precipitate it as limestone and thus remove the source of the problem.

When the pH of a mud is run in the proper range and the carbonate and bicarbonate concentrations are minimized, the mud properties should remain stable and responsive to chemical treatment.

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pH and Alkalinity

Continued

In addition to the filtrate alkalinities, an alkalinity determination is made for the mud (P_m). This test is made in the same way as the P_f test, except whole mud is used rather than filtrate. The purpose of this test is to determine the mud's reserve alkalinity. There are sources of alkalinity, which due to limited solubility of materials such as lime or cement or absorption of hydroxyl ions on solids, are carried as solids in a mud. As the hydroxyl ions in solutions are used up, more hydroxyl goes into solution from these sources and stabilizes the pH.

The water fraction of a mud sample will have the same concentration of hydroxyl ions as the filtrate. If the volume fraction of water in a mud is multiplied by P_f , the result should be the contribution of the water phase to the P_m alkalinity. This number subtracted from P_m is the contribution to alkalinity from the solids. If this number is multiplied by 0.26, the solids contribution to P_m alkalinity is calculated as equivalent free lime concentration in lb./bbl.

$$\text{Free lime, lb./bbl} = .26 \left[P_m - \frac{\% \text{water}}{100} (P_f) \right]$$

Calcium and Magnesium Determinations

Calcium or magnesium ions in a mud have a pronounced effect on behavior of the clays. These ions replace sodium ions on the clays, reduce the degree of hydration, and promote flocculation and aggregation of the clay particles. This leads to increases in yield point, gel strength, and fluid loss of the mud. Many of the organic treating agents are also sensitive to calcium and magnesium concentrations. For these reasons, it is necessary to monitor the concentration of these ions in the mud filtrate.

To determine the combined concentrations of calcium and magnesium in the filtrate, a total hardness test is made. The result of this test is reported as calcium in ppm. If the actual calcium and magnesium concentrations are desired, it is necessary to run a second titration using another indicator specific to calcium. This test gives the calcium concentration and the magnesium concentration can then be calculated. When magnesium is known to be present, both determinations should be made. This is necessary since treatments to remove these two ions from solution are different.

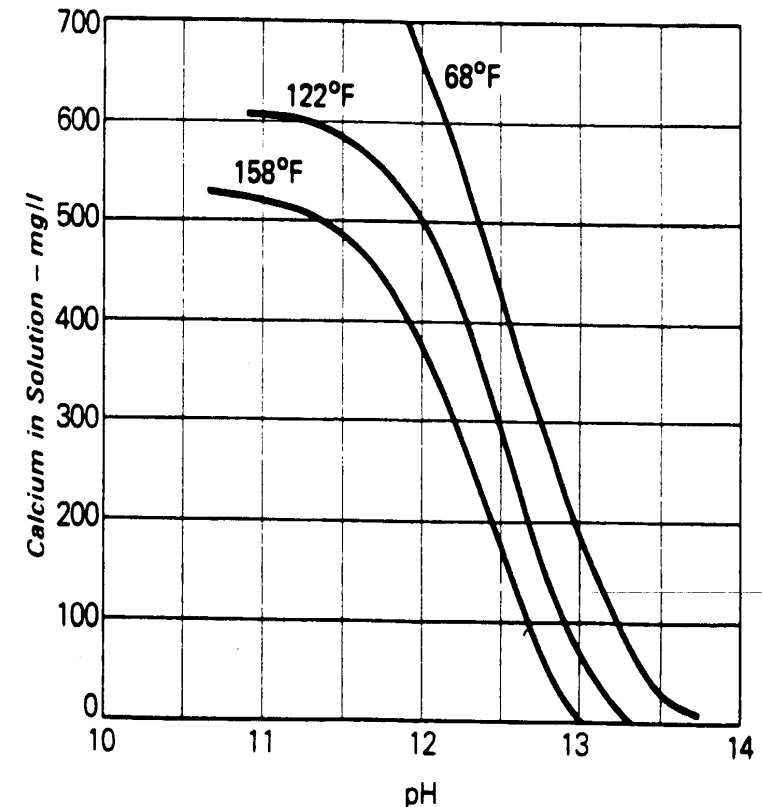
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Calcium and Magnesium Determinations Continued

The solubility of a calcium salt such as gypsum or lime is increased by increased salinity and decreased by increased pH or temperature. As a result, addition of these materials to a mud either as contaminants or intentional additions will result in various calcium ion concentrations in the filtrate. The effect of temperature and pH on the solubility of calcium in fresh water is shown in **Figure 6**. Caustic (NaOH) is sometimes used to suppress the level of soluble calcium in a mud. This technique is often used in lime muds to control the calcium concentration.

The usual method for precipitation of calcium is the addition of soda ash (Na_2CO_3). The calcium is precipitated as CaCO_3 (limestone).

Figure 6
Solubility of Calcium
(a Function of pH and °F)



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Calcium and Magnesium Determinations

Continued

One lb./bbl of soda ash will precipitate approximately 1000 ppm of calcium. This is the same reaction that was discussed in the preceding section on alkalinity control where we were interested in removing the carbonate ion from solution. Obviously, if an overtreatment of soda ash is used to remove calcium from solution, a carbonate problem will occur. Overtreatment will result in high yield point, high gel strength, and fluid loss. In fact, it is possible to go from one problem to the other without realizing what happened, since both the calcium and carbonate ions produce nearly the same changes in mud properties. To avoid this problem, a small amount of calcium (approximately 100 mg/l) should be left in solution

Calcium can also be removed from solution with lignite. This is an expensive way of removing calcium, but it has an advantage in that pretreatment of the mud with lignite will not harm the mud properties. At very high lignite concentrations, an influx of calcium will form a precipitate that can cause an increase in plastic viscosity and yield point. Prolonged use of lignite in such a situation should be avoided. Its use should also be suspended when adding calcium to remove carbonates, since it will interfere with this reaction. Lignite also appears to interfere with the calcium determination. Apparently, some of the particles which have reacted with calcium are small enough to be collected in the filtrate. This calcium, although not free

Continued on next page

Calcium and Magnesium Determinations Continued

to react in the mud, is checked as soluble calcium in the calcium test. In this situation, both calcium and carbonate apparently exist at the same time in a mud filtrate. This is impossible, and simply indicates that the calcium determination is in error.

Magnesium can be removed from solution by the addition of hydroxyl ions. At a pH above 10, essentially all the magnesium is precipitated as insoluble magnesium hydroxide. This precipitate is very fine and has an extremely large surface area. If precipitated in large quantities, it will form a rigid gel. Consequently, concentrations above a few thousand mg/l cannot be precipitated without causing major increases in mud viscosity. Due to its large surface area. It is also capable of physically extracting organic treating agents such as lignosulfonate and CMC from solution. These materials should be added to a mud after addition of caustic and precipitation of the magnesium.

Chloride Determination

Salinity is another important part of the water chemistry of a mud. It is measured by titration of the filtrate for chloride ion concentration and is reported as chloride concentration in mg/l or as sodium chloride (NaCl) concentration in mg/l. The sodium chloride concentration is equal to 1.65 times the chloride concentration.

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Chloride Determination Continued

The salt content of a mud has a great effect on the behavior of the clay solids. The degree of hydration of bentonite is reduced by increased salinity. This results in decreased plastic viscosity and increased fluid loss. When clays are hydrated in fresh water, addition of salt will cause flocculation and increased yield point and gel strength.

Monitoring the chloride content of a mud is a means of detecting a salt water flow or the drilling of salt. It is sometimes possible to detect an increasing trend in chlorides as the formation pore pressure increases. This is one of several indicators of abnormal pressure. Makeup water should also be titrated for chlorides in order to determine whether an increase in filtrate chlorides has come from the formation or from the makeup water.

When the chloride concentration is 20,000 mg/l or higher, prehydrated bentonite should be added for fluid-loss control. Dry bentonite added to such muds will not hydrate sufficiently to give good fluid-loss control.

Pilot Testing

It is usually wise to run pilot tests before attempting to make any major change in mud properties. By pilot testing proposed additions to the mud, costly mistakes in treating the total system can be avoided. Pilot testing can also be used to evaluate in advance the

Continued on next page

Pilot Testing

Continued

performance of a mud under anticipated conditions, such as long-term exposure to high temperature or influx of various contaminants.

Any time a mud problem occurs, pilot testing should be used to confirm the diagnosis. There is often more than one possible cause for a problem. A series of pilot tests designed to cure each possible cause will indicate the best solution. Pilot testing should also be done in advance of increasing the mud density. Mud problems or barite contamination problems can be discovered before any great amount of harm has been done.

A pilot test should simulate as closely as possible the conditions downhole. Temperature, pressure, and shear are all important conditions that affect mud performance. Even the cycling of the conditions that the mud undergoes during circulation may affect its performance. The rate and order of addition of the mud additives also may have an effect on mud properties.

A pilot test accurately indicates the performance of a mud under the conditions that are used in the test. Unfortunately, our pilot test information will not be completely accurate in all cases because the test conditions are not duplications of downhole conditions.

However, the information should serve as a quite useful guide.

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Pilot Testing

Continued

Normally, temperature is the most important condition that affects mud performance. An oven equipped to roll or rotate mud samples will allow heat aging of mud samples under conditions of very mild agitation. Static aging can also be studied with the same oven if we are concerned with barite settling or packer mud performance.

The rolling or rotating test is more representative of the mud being circulated. It is also more rigorous than a static test. It supplies mixing, which is necessary for some reactions in the mud to go to completion.

Properties should be checked both before and after heat aging in order to evaluate initial and aged effects of mud treatment. A sample of the base mud should be carried through the pilot testing conditions to provide reference data.

As a general rule, we should routinely conduct pilot tests in critical situations, looking ahead to higher temperatures and mud densities as we drill deeper. With this data. We should be able to keep ahead of impending mud problems.

Section IV

RELATIONSHIP OF MUD COMPOSITION TO PROPERTIES

Relationship to Mud Composition to Properties

In order to effectively control the properties of a mud, we need to know how specific changes in mud composition will affect the properties. There are normally a number of ways that a mud property can be adjusted to a given value. However, we are usually faced with maintaining several properties within acceptable limits. This means that there is one best way to adjust a mud property and still maintain control of the other properties. In order to accomplish this, we must understand the interrelationship between mud composition and mud properties.

The liquid and solids content of a mud form the foundation which ultimately determines the performance of the mud. Chemical treatment should be thought of as a means of making small or selective adjustments in mud properties and not as the primary controlling component of a mud.

Solids

The primary source of control of rheological and filtration properties is the control of the amount and type of solids in the fluid. The importance of controlling the solids in a mud can not be overly

Continued on next page

Solids

Continued

stressed. This is the basis of all mud treating. Undesirable solids increase drilling costs. They cause reduction in penetration rate, promote lost circulation and differential pressure sticking, and cause high mud costs due to treatment and dilution to maintain necessary mud properties. The normal mud cost for drilling a well is linked very closely to the solids control practice used.

In general, our aim is to minimize plastic viscosity for increased penetration rate, provide sufficient yield point or effective annular viscosity to clean the hole without causing unnecessarily high circulating pressures, and provide sufficient gel strength to suspend barite and cuttings. To fulfill these requirements, we must adjust the flow properties of a mud to handle each situation that is encountered. It is obvious that ideal mud properties for one problem may increase the severity of another. For this reason, there is no standard recipe for an ideal mud composition.

For all except a very few special situations, barite and bentonite are the only solids needed to provide the density, viscosity, and fluid-loss control requirements of a mud. Formation solids that enter the system from the drilling process provide no function that could not be better satisfied by addition of barite and bentonite. As a result, elimination of drilled solids is a primary concern.

Inert Solids

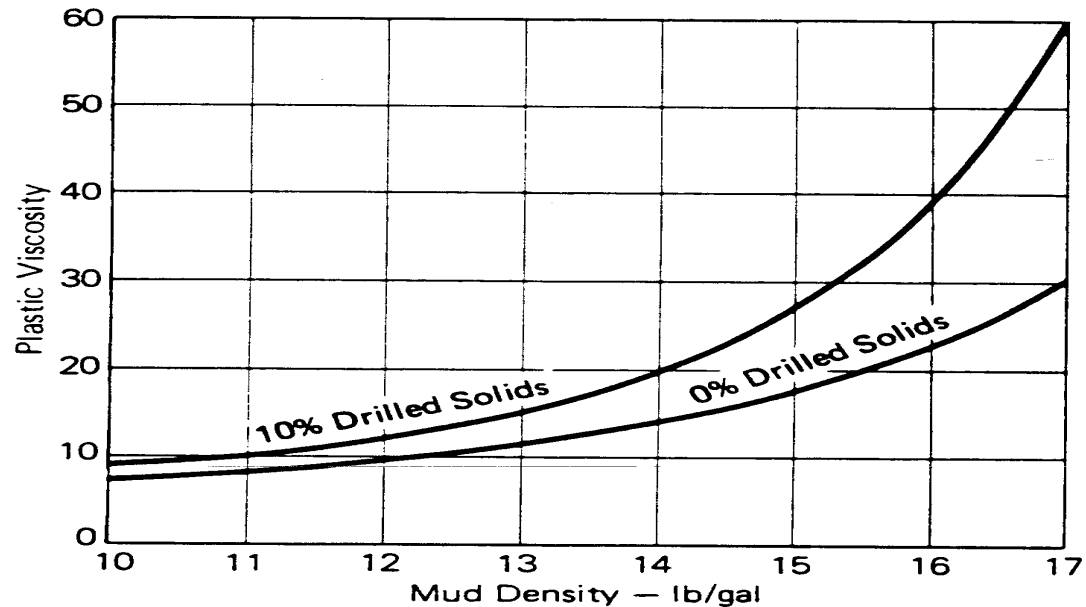
The solids in a mud can be roughly divided into two types, inert and active. The inert solids are those that have very little tendency to react with each other or to a change in environment. These are non-swelling solids which are essentially electrically uncharged and easily dispersed. They consist of such materials as sand, silt, limestone, feldspar, and barite. With the exception of barite, these solids are undesirable in a mud. They increase the plastic viscosity and crowd the system so that more desirable solids cannot be added. They do little to reduce fluid loss and actually cause the filter cake to be thicker. Since they are not hydrated, they cause the filter cake to be dry and brittle with a high coefficient of friction. These are poor qualities to prevent differential pressure sticking.

As the total volume of solids in suspension is increased, the mechanical resistance to flow is increased. This causes an increase in the plastic viscosity. As the solids become crowded' the plastic viscosity increases quite rapidly. The difference in plastic viscosities between muds containing no drilled solids and 10 percent drilled solids is shown in **Figure 1**. This curve assumes completely inert drilled solids. If the drilled solids hydrate and increase in volume, the plastic viscosities will be even greater. This shows the need for maintaining a low solids content in a mud.

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Inert Solids Continued

Figure 1
Effect of Inert Drilled Solids
on Plastic Viscosity



Active Solids

The active solids are those that have electrically charged surfaces and are reactive with their environment. Due to their charge distribution, they can interact with one another to form a gel structure within a fluid. Most of the active solids also have the ability to hydrate in water.

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Active Solids

Continued

Clays are the primary source of active solids in a drilling fluid. Due to their characteristics, they exhibit a dominant role in determining the rheological and filtration properties of a mud. For this reason, it is necessary to understand basic clay chemistry in order to properly control water-base muds.

In most muds, there are two primary sources of clay solids: bentonite, which is added intentionally, and native clays, which enter the mud through dispersion of drilled solids. The native clays are a combination of several clay minerals that exhibit varying degrees of hydration and dispersibility. Different shales contain different amounts of the various clay minerals. Consequently, some shales exhibit a greater “mud-making” ability than others.

The amount of water adsorbed on clay platelets (and hence swelling) is controlled by both the type of clay and the exchangeable cation on the clay. Bentonite has a smaller particle size, higher charge density, and greater ability to swell in water than the other types of clays. This makes it a better viscosifier and fluid loss control agent.

When a bentonite particle is added to water, it absorbs water on the surfaces of the individual platelets that make up the particle. This increases the distance between platelets and causes the particle to grow in size. In this expanded state, either thermal or mechanical

Continued on next page

Active Solids

Continued

agitation will cause the individual platelets to disperse in the water. The water adsorbed on the platelet becomes a part of the platelet and greatly increases its size.

We started with one particle and through the process of hydration and dispersion created many particles whose total volume and surface area are many times greater than the original dry particle. Since the apparent volume of solids has increased, the plastic viscosity will be increased. Due to the increased surface area of the electrically charged platelets, the linking of particles is enhanced. This will cause an increase in yield point, gel strength, and low shear rate viscosity. Since these platelets are small, thin, and highly hydrated, they are exceptionally good for fluid loss control and prevention of differential pressure sticking.

These characteristics make bentonite, hydrated in fresh water, the best single mud additive that we have. By controlling the amount we use and treating to control its natural tendency to flocculate, we can construct a mud which will basically fit any requirement.

We should minimize the amount of native clay solids in a mud and rely on bentonite for control of the flow properties. This allows us to carry a minimum amount of solids in a mud and simplifies treatment of the mud. The amount of bentonite required should be based on the required yield point. Gel strength. And filtration control. Additions

Continued on next page

Active Solids

Continued

of bentonite should be made slowly and both the “in” and “out” properties checked. Bentonite increases in yield with both time and temperature. If the mud going in is adjusted to the desired properties, it will come out at higher properties due to further dispersion from temperature down hole. An increase in both the plastic viscosity and yield point will be observed from temperature dispersion and hydration of clay solids. This is in contrast to the symptoms of temperature flocculation where only the yield point and gel strength are increased.

Large amounts of solids in a mud will decrease the fluid loss but will also cause thick filter cakes to be deposited. This is contrary to our basic objective of maintaining thin filter cakes. To avoid this problem, we should always attempt to maintain a minimum amount of total solids in a mud. We should minimize solids that form high permeability cakes and add solids that form low permeability cakes.

Basically, this means we should minimize the amount of formation solids in a mud and add bentonite. The formation solids are normally poorly hydrated and dispersed, and control fluid loss only by building excessively thick filter cakes of poor quality. For reasons of economy, muds in the range from 10 to 11 lb./gal are often built with native solids. Many times this is a false economy, since filtration related problems often occur. **Figure 2** shows the difference in cake

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Active Solids

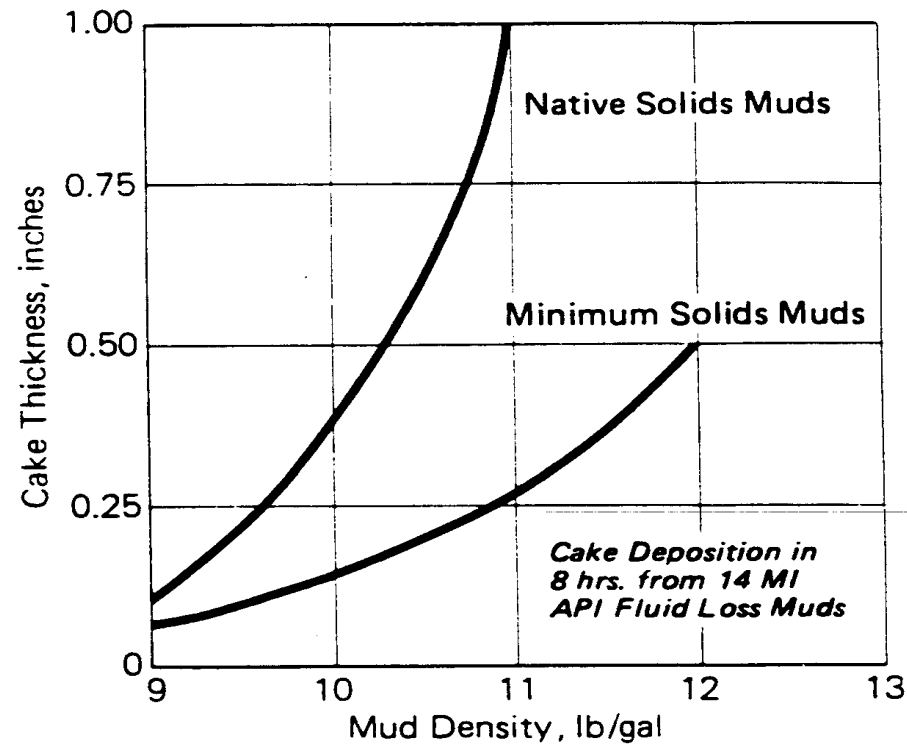
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thickness between native solids muds and minimum solids (bentonite and barite) muds with the same fluid loss.

Bentonite is one of the best filtration control agents we have. It is quite temperature stable and. Considering its low cost, it seems only natural that it should be the basis of filtration control in water-base muds. When used properly, it has the capability to solving most filtration problems. The ability of bentonite to control filtration is based on its naturally small, plate-like particles, and high degree of hydration. Since these characteristics depend on the chemical environment in which bentonite is placed, most of our efforts in treating a mud are based on control of this environment.

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Figure 2
Effect of Solids on Cake Thickness



Effect of Salinity on Clays

The ionic content of water affects the hydration, dispersion and flocculation behavior of clay particles. As the salinity is increased the degree of hydration is decreased. This is caused by the cations

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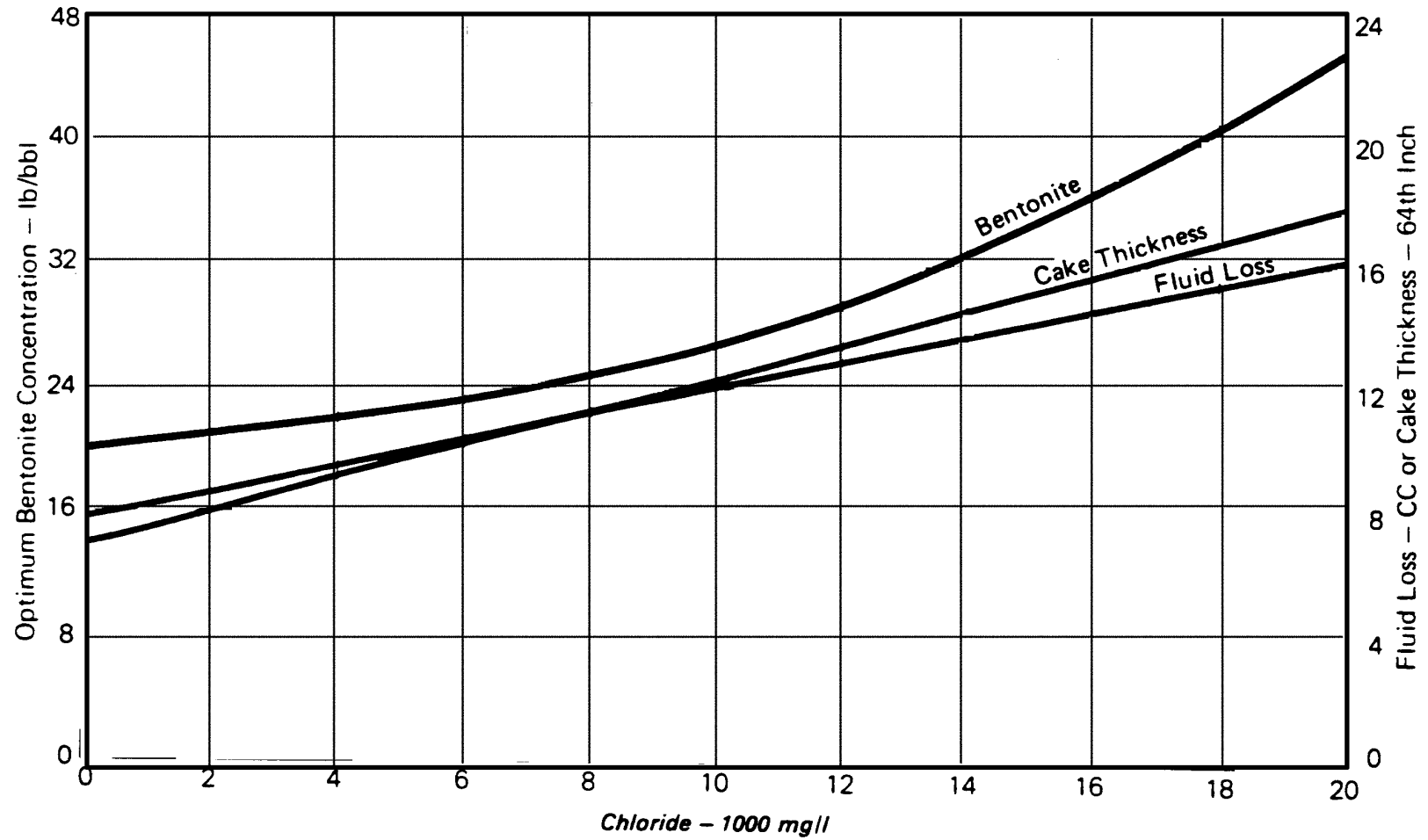
Effect of Salinity on Clays Continued

in solution pushing the exchange cations closer to the surface of the clay platelet. This causes the water layer bound by the clay surface and the exchange cations to be thinner. As a result the plastic viscosity will be less and the fluid loss will be greater than when the clay is hydrated in fresh water. Since the water layer is thinner, the platelets can come closer to one another and tendency to flocculate will be greater.

Increased bentonite additions are required to help offset the effects caused by increased salinity. Approximate dry bentonite additions required for water salinities up to 20,000 mg/l chloride are shown in **Figure 3**. Concentrations of bentonite shown on this curve result in suspensions of about equivalent viscosities. The fluid loss and cake thickness both increase with increasing chloride concentration as shown on the graph. These bentonite contents were selected so that the harmful effects of salinity on bentonite performance would be equally shared by both fluid loss and cake thickness. A higher bentonite content should result in lower fluid loss but a much thicker filter cake. This graph should be used only as a rough guide. Exact bentonite content will depend on desired flow properties and filtration requirements.

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Figure 3
Approximate Dry Bentonite Requirements in Various Salinities



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Effect of Salinity on Clays

Continued

These data clearly show that dry bentonite added to muds with chloride concentrations above about 10,000 mg/l will not hydrate sufficiently to give good filtration control. In these muds, prehydrated bentonite should be used.

Prehydration of Bentonite

Prehydrated bentonite should be prepared in fresh water. Any salt, calcium, caustic, or chemical treating agent will decrease the amount of hydration and dispersion that can be obtained. The hydration of bentonite increases with increased time, temperature, and agitation. If possible, about 6 to 8 hours should be allowed to insure good hydration. High shear mixing aids in hydration and dispersion.

After the hydration period is complete the slurry should be treated with 2 to 8 lb./bbl of lignosulfonate and the pH increased to 10 by adding caustic. This causes the bentonite to maintain a high degree of hydration after it is subjected to a high chloride environment. Good fluid-loss control can be achieved with this technique, even in salinities up to saturation.

When prehydrated bentonite is used, the concentration required in the mud is approximately that which is required in a freshwater mud. However, it should be prepared with as high a concentration as possible and still remain pumpable. Otherwise, it may be a source of

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Prehydration of Bentonite

Continued

excessive dilution when added to a weighted mud. It is usually possible to mix 35 to 45 lb./bbl. After addition of lignosulfonate, it becomes less viscous and more easily pumped. When mixing subsequent batches in the same tank, care should be taken to completely empty the tank each time. Otherwise, the lignosulfonate remaining in the tank will inhibit the hydration and dispersion of the next batch.

When prehydrated bentonite is added to a saltwater mud, it increases the yield point more than the same amount of bentonite would in fresh water. Lignosulfonate can normally be used to control yield point. However, at the higher levels of salinity, lignosulfonate does not work as well and small amounts (0.1 to 0.2 lb./bbl) of CMC can be used quite effectively. Greater concentrations of CMC will increase the plastic viscosity.

This is the same situation that occurs when a saltwater flow is encountered or when salt is drilled with a freshwater mud. Severe flocculation problems will occur unless the mud has been pretreated with rather large amounts of lignosulfonate (6-10 lb./bbl).

Effects of Calcium and Magnesium on Clays

Calcium and magnesium have a greater cation exchange replacing power than sodium. When added to a bentonite suspension in relatively small concentrations, they have the ability to displace part of the sodium from the exchange sites on the clay platelets. Due to their greater charge, calcium and magnesium are held closer to the surface of the clay platelets. This causes the adsorbed water layer to be thinner and decreases the repelling forces between the negatively charged platelets. For this reason, relatively small amounts of calcium or magnesium cause great changes in the performance of clays. When bentonite is added to water containing more than a few hundred ppm of either of these ions, the degree of hydration is greatly reduced and the tendency to disperse is inhibited. As a result, very little viscosity is developed and the fluid loss is quite high.

At one time, gyp and lime muds were commonly used to take advantage of the inhibiting behavior of calcium. Lime muds contain from 100 to 300 mg/l calcium in the filtrate and gyp muds contain 400-1200 mg/l calcium. Due to their inhibitive nature, these muds will tolerate a high concentration of formation solids before becoming too viscous to pump. The high solids content and high fluid loss of these muds made them poor from the standpoint of differential pressure sticking. Also, the high solids content and

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Effects of Calcium and Magnesium on Clays

Continued

flocculation tendency of calcium caused severe gelation problems at high temperature. Because of these problems, lime and gyp muds declined in use. In recent years, improved solids removal devices and organic treating agents have solved these objectionable problems and made these muds more attractive.

When the calcium or magnesium concentration in a mud is suddenly increased, the mud undergoes some drastic changes. The clays dehydrate and flocculate. This causes a decrease in plastic viscosity and an increase in yield point. Gel strength, and fluid loss. The severity of these problems is a function of the concentration of clay solids, the amount of calcium introduced into the system, and the concentration of lignosulfonate in the mud. In lightly treated muds. 100 to 200 mg/l of calcium may completely flocculate the mud. This often occurs from cement contamination in surface hole muds.

Flocculation from any cause is always aggravated by a high solids content. Maintaining a mud with a minimum amount of clay solids is the first line of defense against calcium contamination. If the mud has high concentration of lignosulfonate, it will behave like a prehydrated bentonite suspension. The lignosulfonate will protect the bentonite and minimize the amount of dehydration and

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Effects of Calcium and Magnesium on Clays

Continued

flocculation that occurs. This protection is limited to calcium concentrations below about 2000 mg/l.

Usually a saltwater flow will contain both calcium and magnesium. The magnesium is precipitated by the hydroxyl ion. A rapid decrease in pH will occur. This necessitates a high starting pH to minimize the effects of magnesium influx. The precipitate that forms will

physically extract organic treating agents. Fresh lignosulfonate should be added to replace that which is removed.

Lignite also offers some protection from an influx of calcium. One lb./bbl of lignite will precipitate about 200 mg/l of calcium. If the calcium influx is not too great. This is a good way to handle it without upsetting the mud. However. The precipitate will build viscosity if more than about 6 to 10 lb./bbl of lignite is precipitated.

When the total hardness reaches a level where precipitation is no longer practical or when the influx is sustained for a prolonged period of time, (such as drilling gypsum or anhydrite), it is necessary to convert to a calcium-based mud. In this state, the clay platelets have aggregated face-to-face like a deck of cards. With a smaller total number of particles, the yield point and gel strength are less and the fluid loss greater. The mud may require addition of materials that will build viscosity and decrease fluid loss in the presence of

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Effects of Calcium and Magnesium on Clays

Continued

calcium. The concentration of calcium in the mud and the bottom-hole temperature will dictate what materials can be used.

At temperatures below 225°F, polymers such as starch, CMC, and Xanthan polymer can be used to build viscosity. Starch and CMC will also reduce the fluid loss. At high temperatures, materials such as attapulgite and asbestos are required to build viscosity. However, these materials will not control fluid loss.

Cement Contamination

Cement affects mud properties in essentially the same manner as lime. As cement goes into solution it raises the pH to values above 12. The calcium concentration is normally, in the range of 100 to 300 mg/l. These values are fixed by the limit of solubility of the cement. Consequently, most of the cement remains as small particles in the mud. This is evidenced by a high P_m .

In cement contamination, both the calcium and the ultra-high pH are responsible for the flocculation of clay solids. Therefore, both need to be controlled. The standard treating agents are sodium bicarbonate and SAPP. Both of these materials reduce the pH and precipitate or sequester the calcium ions. Overtreatment with either material is as harmful as cement to the mud properties. The pH, alkalinities, and calcium should be monitored to avoid overtreatment.

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**Cement
Contamination**
Continued

When the P_m is reduced to about 3 times the P_f treatment should be suspended. Lignite and lignosulfonate are both useful in treating a cement-contaminated mud. Both are acid and will reduce the pH, and both will deflocculate and thin the mud. In addition, Lignite will also precipitate calcium. Pretreatment of the mud with these additives is also quite beneficial and recommended. They will not upset the mud properties as will SAPP and bicarbonate. Do not use alkaline materials such as soda ash or sodium tetraphosphate.

Since most of the cement is carried in the mud as particles, treating will only remove that which is in solution and allow more of the cement particles to go into solution. Consequently, the problem will reoccur repeatedly until all of the cement has gone into solution and been treated out chemically. This is a very slow process and often leads to eventual overtreatment. If the cement particles are removed from the mud mechanically, the mud can be restored to original condition much quicker. Fine-screen shakers should be used to remove as much cement as possible. Then the centrifuge can be used to remove the small particles as well as the contaminated water and clay solids. Often, it is desirable to dump as much of the highly contaminated mud as possible.

Emulsified Oil

Emulsified oil acts as small, inert solids in a mud and increases the plastic viscosity. When a mud becomes crowded with solids, as in the case of a high weight mud, the addition of oil will cause significant increases in plastic viscosity. This effect largely determines the amount of oil that can be added to a mud. By removing as much of the drilled solids as possible, some room can be made for oil. When mud weight exceeds 17 lb./gal, only 2 to 4 percent oil can be added without producing excessively high plastic viscosities and yield points.

Significant decreases in fluid loss are achieved with increasing oil concentration up to about 5 volume percent; at higher concentrations fluid loss declines more gradually. Emulsified oil droplets act in much the same manner as colloidal particles in plugging fine pores in the filter cake and reducing cake permeability. These droplets deform under pressure and seal pores that would not be completely sealed by a rigid particle.

Oil reduces the friction between the filter cake and pipe more than other additives and fluid-loss control agents. The oil droplets apparently occupy space in the surface of the filter cake that would otherwise be occupied by solids that have a much higher coefficient of friction on steel. This unique quality makes oil one of the best additives that we have to prevent differential pressure sticking.

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Emulsified Oil

Continued

In order to function effectively as a differential pressure sticking additive, the oil must be well emulsified. This requires a great deal of shear to reduce the oil to fine droplets, and a stabilizing film around the droplets to keep them from coalescing. Stable emulsions can usually be formed without the aid of a chemical emulsifier when dispersed clays, lignite, and lignosulfonate are present.

Operationally, it is best to add oil slowly and directly into the pump suction. In this manner, a high degree of emulsification is accomplished in the first circulation cycle with uniform distribution and no loss of oil.

When oil is added slowly and continuously, it often appears to increase penetration rate and prevent bit balling. These effects seem to occur only when the oil makes its first pass through the bit and before it becomes completely stabilized in an emulsion.

Treating Agents

After the solids content of a mud has been properly adjusted in type and amount, selective adjustments in mud properties can be made with special treating agents. These additives fit roughly into three categories: deflocculants, fluid-loss control agents, and viscosifiers.

Deflocculants (Thinners)

Any material that will deflocculate a clay suspension is normally referred to as a thinner. Flocculation is caused by a positive charge site at the edge of a clay platelet linking to the negative surface of another platelet. The primary effect of a thinner is believed to be a neutralization of the positive charge, which destroys the ability of the platelets to link together in this manner. This renders the platelets completely negatively charged and causes them to repel one another, or to avoid contact. Thus, the resistance to flow of the suspension is reduced.

Thinners are used to reduce the yield point, gel strength, and low shear rate viscosity. They are not used to reduce the plastic viscosity since it is a function of the total volume of solids in suspension and not concerned with the linking of these particles.

The tendency of a mud to flocculate is increased by:

1. A high solids content, especially a high active solids content.
2. A high electrolyte content such as salt or soluble calcium compounds.
3. High temperature.

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**Deflocculants
(Thinners)**
Continued

To be effective, a thinner must be capable of performing under these conditions. Two of the first thinners used in muds, phosphate (sodium tetraphosphate) and quebracho (sodium tannate), have deficiencies in all of these areas.

Phosphate is a very efficient thinner at low temperature in freshwater muds. Addition of 0.1 to 0.2 lb./bbl will completely deflocculate a mud. However, it will not perform at high salt concentrations or in the presence of calcium. It is actually a sequestering agent for calcium and is thus depleted in a calcium environment. At temperatures above 180°F, it reverts to orthophosphate, which is a flocculating agent.

Quebracho is also an effective thinner, requiring only 1 to 2 lb./bbl to deflocculate a mud. For best results, it should be used at a pH above 11. It is effective in lime muds or cement-contaminated muds, but is not effective at higher calcium levels or in high salt content muds. It is not capable of deflocculating at temperatures above 225°F.

The best all-purpose thinner is chrome lignosulfonate. It has a much greater tolerance for salt and calcium than the other thinners and will deflocculate at temperatures in excess of 350°F. It is altered by high temperatures, however, and has a rather short life expectancy at 350°F. It is thought that polymerization takes place at high

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Deflocculants (Thinners)

Continued

temperature, making the material less soluble and less effective as a deflocculant. This makes it difficult to assign a value to its temperature stability. At 350°F, degradation takes place and carbon dioxide and hydrogen sulfide are liberated in a reasonably short time. These by-products actually appear to be more detrimental to the mud than the loss of active lignosulfonate. A high pH, in the range of 10 to 11, helps to cancel the effects of CO₂ and H₂S and increases the time that lignosulfonate will function effectively at the elevated temperatures. The active lignosulfonate content appears to be diminished about 2 lb./bbl after aging 16 hours at 300°F.

The concentration of lignosulfonate necessary to deflocculate is a function of the severity of the factors that promote flocculation. In an uncontaminated freshwater mud at temperatures below 200°F, about 1 to 2 lb./bbl is sufficient. At 300°F, approximately 4 lb./bbl is required. In seawater muds. From 6 to 10 lb./bbl is necessary to effectively control yield point and gel strength.

Sufficient lignosulfonate concentration is indicated when the gel strengths are low and do not change appreciably between measurements at the suction and flowline. If the gel strength measured at the flowline is significantly higher than the gel strength measured at the suction, flocculation is occurring downhole. This could be caused by either a lignosulfonate deficiency or a

Continued on next page

**Deflocculants
(Thinners)**
Continued

contamination problem. If the gel strength does not respond to a small lignosulfonate addition, a problem in water chemistry is indicated. The filtrate analysis should be carefully studied to help diagnose the problem.

Lignite is another product that is sometimes used as a thinner. It is more resistant to thermal degradation than lignosulfonate, but it is less effective as a deflocculant at high temperatures. This fact is sometimes not recognized. When the flow properties are measured after allowing the mud to cool, the yield point and gel strength will be considerably less than if they were measured at downhole temperature. This can lead to the mistaken belief that the mud is also deflocculated downhole. Lignite is not an effective thinner at temperatures above 250°F.

**Fluid-Loss Control
Agents**

Several types of materials are used to control fluid loss in water-base muds. Basically, these materials reduce the fluid loss either indirectly by acting on the clay solids to improve their filtration control characteristics, or directly by acting as a colloid or water thickener. In most cases they affect the flow properties as well as the fluid loss.

Basically, lignosulfonate and lignite are used to improve the filtration control performance of bentonite. When bentonite flocculates, it

Continued on next page

**Fluid-Loss Control
Agents**
Continued

becomes less effective as a filtration control agent. Lignosulfonate and lignite deflocculate the bentonite, thereby reducing the fluid loss. Contaminating ions, such as calcium and magnesium, not only cause flocculation but also dehydration and aggregation of bentonite. Lignosulfonate appears to protect the bentonite from these harmful effects and lignite precipitates the ions, thereby removing the source of the problem. Consequently, these additives are quite effective at high temperature or in the presence of calcium and magnesium. Since their ability to control fluid loss is tied directly to the colloidal solids content of a mud, care must be taken to provide sufficient bentonite that is well hydrated and dispersed.

Lignite is different from lignosulfonate in that it also acts as a colloidal material. In high weight muds where additional bentonite cannot be used because of viscosity considerations, addition of lignite will reduce fluid loss without causing excessive increases in viscosity. A pound of lignite will reduce the fluid loss approximately the same amount as a pound of bentonite.

Causticized, or prereacted, lignite is more expensive than ordinary lignite but is not substantially different in performance. The solubility of lignite is increased as the pH is increased. This makes the causticized lignite appear more soluble in water than ordinary lignite; however, caustic added with the lignite will attain the same results.

Continued on next page

**Fluid-Loss Control
Agents**
Continued

Some lignite products are neutralized with potassium hydroxide and blended with a chromium or zinc compound. This supposedly causes them to inhibit shale dispersion and increase the temperature stability of a mud. Both potassium and the heavy metals are detrimental to fluid-loss control. Any improvement in shale inhibition or temperature stability is questionable.

Natural lignite has a pH of about 4.5, which makes it a far superior material for treating a cement-contaminated mud than the causticized lignites. In general, it is cheaper on a cost-performance basis than the specially prepared lignite products.

A number of water-soluble polymers are used to control fluid loss in situations where it is impractical or undesirable to use bentonite. All these materials have a limited range of application and should be considered special-purpose products.

Starch is one of these polymers. It is primarily used in brine muds at relatively low temperatures. Starch is one of a few products unaffected by water salinity or hardness. It thickens water, thereby deriving most of its fluid-loss control. As a consequence, it increases the plastic viscosity and tends to reduce penetration rate. A starch solution thins with temperature at the same rate as water. This leads to reduced viscosity downhole and a loss of hole-cleaning ability.

Continued on next page

**Fluid-Loss Control
Agents**
Continued

Thermal degradation begins at about 180°F and increases to a prohibitive rate at a temperature of 250°F.

Starch is used in concentrations of 2 to 6 lb./bbl. Due to its viscosity-building ability, it is often used as the source of both viscosity and fluid-loss control. It is subject to bacterial degradation and must be used with a preservative except in saturated salt water or at a pH above 11.5.

CMC is another polymer type material used for fluid-loss control. It comes in three grades: technical, regular, and high viscosity. The technical grade is a low viscosity material that contains salt and is about 75 percent pure. The regular and high-viscosity materials are nearly 100 percent pure and differ only in the chain length of the polymer. High viscosity CMC has a longer chain length than regular CMC and will build about twice as much viscosity. The ability of the three grades to control fluid loss is essentially proportional to their ability to build viscosity.

At low concentrations, CMC deflocculates clay suspensions in much the same manner as lignosulfonate. This results in a reduction in fluid loss as well as in yield point. As the CMC concentration is increased, the viscosity of the water is increased and further reduction in fluid loss is achieved. If a high yield point and lower

Continued on next page

**Fluid-Loss Control
Agents**
Continued

plastic viscosity are desired, addition of CMC is detrimental, since it has the tendency to deflocculate and to build plastic viscosity.

As water salinity is increased it becomes more difficult to hydrate and expand the CMC molecule. Extremely high shear mixing is required. At salinities above 50,000 mg/l chlorides, CMC rapidly becomes less effective as a fluid loss control agent. It also becomes ineffective at calcium concentrations above 100 mg/l.

CMC, like other organic additives, has a time rate of thermal degradation which makes it difficult to identify a breakdown temperature. As temperature is increased above 250°F, the rate of degradation accelerates very rapidly until almost complete degradation is achieved in 16 hours at 300°F. Fluid-loss control at temperatures above 250°F should be considered only as short-term control.

When CMC is thermally degraded, CO₂ is formed. In time, a carbonate and bicarbonate concentration can build in the mud and lead to a high yield point and gel strength. Small additions of lime may be necessary to control this problem.

In summary, the various grades of CMC share a common shortcoming with starch. They build viscosity in order to control fluid

Continued on next page

**Fluid-Loss Control
Agents**
Continued

loss. This factor severely limits their use in high weight muds. The thermal instability and sensitivity to salinity and water hardness also limit the use of this material.

Another type of water-soluble polymer used for fluid loss control is polyacrylate. It is one of many different polymers that can be grouped under the basic classification of vinyl polymer. These materials are somewhat more thermally stable than CMC or starch, but they are extremely sensitive to calcium. Calcium concentrations above 200 mg/l will cause excessively high gel strengths that cannot be controlled.

These polymers are similar to other vinyl polymers used as clay extenders. At low concentrations (up to about 0.1 lb./bbl) they are flocculants. At higher concentrations they deflocculate and increase the viscosity of the water, thus reducing the fluid loss. To avoid flocculation, they are added at higher concentrations (0.5 lb./bbl) on initial treatment. When used in this application, they actually break the mud over to a deflocculated system. Both clay solids and calcium must be kept to a minimum when using these polymers.

Viscosifiers

Viscosifiers are necessary in muds for two primary reasons: to suspend barite and to increase cuttings carrying capacity. These two functions are carried out by increasing the yield point and providing

Continued on next page

Viscosifiers

Continued

gel strengths of about 2 to 4 lb./100 sq. ft. Normally, bentonite performs these functions without the aid of supplemental additives. Special-purpose viscosifiers are usually limited to situations where bentonite is not well suited (due to high electrolyte content) or where a low-solids mud is desired. Some of these materials such as starch, CMC, and Xanthan polymer build viscosity directly. Others, such as the vinyl polymers, act indirectly by increasing the yield of bentonite. The use of starch and CMC as fluid-loss control agents was discussed in the previous section. Their limitations as viscosifiers are essentially the same as for fluid-loss control. However, temperature appears to have an even greater adverse effect on their viscosifying ability. A very rapid loss of viscosity occurs at temperatures above 200 °F.

Xanthan polymer is another material that increases viscosity when added to water. It is a long-chain polymer that increases the yield point much more than the plastic viscosity. This is a very desirable characteristic for a viscosifier. Good hole cleaning can be attained without high viscosities at the bit and reduced penetration rates. It can be cross-linked in fresh water with the addition of chromic chloride. This produces even higher yield points.

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Viscosifiers

Continued

Xanthan polymer is not greatly affected by electrolyte content. It will build viscosity nearly as well in salt water as in fresh water. One difference is that it cannot be effectively cross-linked in salt water. It thermally degrades quite rapidly at temperatures above 250°F. Like other polymer solutions, it decreases in viscosity with increased temperature. The viscosity at 250°F is only one-fourth of the viscosity at 75°F. This can account for great loss in hole cleaning ability even before degradation occurs. It is sometimes used with small amounts of bentonite (up to 10 lb./bbl) to help offset this temperature-thinning effect. Bentonite will flocculate with increased temperature, making up for the loss in viscosity of the polymer.

Unlike starch and CMC, Xanthan polymer has poor fluid-loss control ability. If an API fluid loss below 30 cc is desired, a fluid-loss control additive is needed. Small amounts of prehydrated bentonite help in this respect as well as in improving the temperature stability of the mud.

The vinyl polymers derive their viscosifying ability by cross-linking clay particles, causing an increase in yield point and gel strength. The polymer molecules apparently adsorb on positive charge sites on the clay platelets. If one molecule is attached to two or more particles, a state of artificial flocculation exists and increased yield point and gel strength will occur.

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Viscosifiers

Continued

The degree of flocculation is quite sensitive to polymer concentration and to clay content. As the concentration of polymer is increased in a dispersed bentonite suspension, the yield point and gel strength will increase until maximum cross-linking occurs. As the concentration is further increased, the yield point and gel strength will decrease until no cross-linking occurs. This apparently happens as a result of polymer molecules adsorbing on all linking sites to the extent that no two particles share the same polymer molecule. Since the concentrations of polymer and clay solids must be matched to achieve maximum results, addition of either to the system will cause a pronounced shift in the flow properties.

In a bentonite suspension of 10 to 15 lb./bbl, approximately 0.05 lb./bbl of maleic anhydride-vinyl acetate copolymer is required to give maximum cross-linking. Approximately 0.1 lb./bbl will deflocculate the system and give minimum yield point and gel strength. As formation clay solids or barite are added, the maximum and minimum cross-linking concentrations of polymer are increased. At the maximum cross-linking point, the yield point and gel strength will be greatly increased as the solids content is increased. This necessitates careful control of solid content either by mechanical removal or dilution.

Continued on next page

Viscosifiers

Continued

When high molecular weight sodium polyacrylate is added to a system for fluid loss control, its effect is additive to that of the maleic anhydride-vinyl acetate copolymer. If the system is at the point of maximum cross-linking, the high molecular weight sodium polyacrylate will cause deflocculation as though more maleic anhydride-vinyl acetate copolymer had been added. As a result, relatively low yield points and gel strengths will result. This is not totally the way a weighted polymer mud is run. It is an extremely sensitive system and consequently very difficult to run with stable mud properties. It is quite sensitive to temperatures above 225°F. At elevated temperatures, severe flocculation may occur downhole without significant differences in properties at flow line temperature being observed.

The use of these polymers to extend the yield of bentonite is limited to fresh water. They will not work in salt water or in the presence of calcium at concentrations above 200 mg/l. If calcium is introduced into the system, extreme gelation will occur.

Emulsifiers, Surfactants, and Lubricants

A number of special-purpose additives are used in muds to emulsify oil, reduce torque and drag, and improve the lubricating qualities of the mud. In general, these additives have very limited utility and are often misused.

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**Emulsifiers,
Surfactants, and
Lubricants**
Continued

Chemical emulsifying agents are normally not necessary in a mud because of the ability of colloidal solids, lignite, and lignosulfonate to stabilize an oil-in-water emulsion. Only when these materials are not present in a mud should the addition of an emulsifier be considered. Due to the difficulty of emulsifying oil in a brine, an emulsifier may be necessary in some cases.

Detergents have been extensively used in drilling muds for a variety of reasons ranging from general mud conditioning to hole stabilization. They supposedly reduce torque and drag, eliminate balling of bits and stabilizers, help in solids removal, and a number of other things. Detergent is such a weak surface-active agent that it probably cannot perform any of these functions at the recommended concentrations. At quite high concentrations (3 to 5 lb./bbl), there is some evidence that it helps prevent shale cuttings from sticking to each other and to bits, stabilizers, and the drill string. Lower concentrations appear to be a complete waste of money. Even at the higher concentrations, the cost may outweigh the benefits.

A 30-mol ethelene oxide adduct of phenol, a more powerful surface-active agent, has also been used extensively in mud. It is a nonionic surfactant that adsorbs on the surface of clay solids. In this condition, the clay solids are less active and appear to disperse less easily. This helps to prevent gelation and may also help in

Continued on next page

**Emulsifiers,
Surfactants, and
Lubricants**
Continued

preventing balling. At temperatures above about 200°F it is insoluble. As it comes out of solution in a high solids mud, high viscosities may develop which cannot be controlled. In general, surfactant muds are quite sensitive to temperature and are somewhat unpredictable.

A number of special lubricants on the market are supposed to reduce torque, drag, and pipe sticking. Claims for these products usually are far greater than their performance. Only after careful field testing and analysis of performance should they be placed in general use. Even then, the product should be checked periodically to see if it has been changed. Most torque and drag problems are mechanical in nature and are not going to disappear upon addition of any mud additive.

In summary, all these products are special-purpose additives. They should be used and evaluated only for a specific reason. They are high-cost materials and should never be used indiscriminately. They do not take the place of good mud and drilling practices.

Section V

DRILLING PROBLEMS

Drilling Problems

A number of major drilling-problems are directly related to the drilling fluid and drilling practices. Mud is a useful tool in working on these problems, but should not be considered the exclusive controlling factor. Solution to these problems often requires adjustments of mud composition, mud properties, and operational procedures such that all facets of the problem are relieved.

Lost Circulation

Lost circulation is defined as the loss of whole mud to a formation. It results from two basic causes:

1. Seepage loss to vugular zones, coarse gravel beds, and shell deposits.
2. Hydraulic fracturing.

It is necessary to identify which of these two causes of mud loss we are trying to combat, because the means of their prevention and cure are quite different.

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Lost Circulation

Continued

Loss of mud to vugular or cavernous zones and to coarse beds of gravel or shell is a natural consequence of the solids in a mud being unable to bridge the openings in the rock. Consequently, the mud is able to flow through networks of the voids and be lost from the circulating system. In shallow, unconsolidated sands or gravel beds, addition of bentonite to thicken the mud is often sufficient to stop or restrict the losses to acceptable levels. If this does not succeed, coarse, fibrous material is added. Cottonseed hulls, the least expensive coarse material available, is adequate for this application. When coarse material is required, it is best to mix batches of approximately 100 bbls rather than to add the coarse material to the entire mud system. This reduces waste of the material and allows higher concentrations to be placed opposite the thief zone. High concentrations of lost circulation material (LCM) in the entire mud system may thicken the mud to the point of causing pressure-induced fracturing and thus compounding the problem. When inexpensive muds are in use, it is often cheaper to drill with partial returns or seepage losses than to try to stop the loss with LCM. When an adequate water supply is available, it is sometimes possible to drill long intervals without returns. The voids in cavernous formations are often large enough to accept cuttings and thus allow the hole to be cleaned without returns to the surface. In

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Lost Circulation

Continued

order to drill without returns, the open-hole section must be competent enough to "stand up" with a reduced mud column. In this situation control of formation pressure is, of course, not possible and must be taken into account.

When other means of lost returns control have not worked, cement is sometimes used. It should not be used unless the depth of the thief zone is known. The bottom of the drill string should be 30 to 50 feet above the thief zone so that the cement will move down the hole instead of up around the pipe. If partial returns are being obtained, the rams should be closed just prior to displacing cement from the pipe, so the cement will be forced down the hole and not allowed to "flash set" around the pipe.

It should be noted that some lost circulation zones cannot be cured within economic reason. In these cases, economics dictate that the well be plugged and abandoned. In many cases, the rig has been skidded and a second hole drilled without difficulty.

The most prevalent type of lost circulation is that caused by pressure-induced fracturing. When the combination of mud weight and pressure due to circulating the mud, or pressure surge from pipe movement, causes a total pressure opposite a formation which is greater than the strength of the rock, a fracture will develop in the

Continued on next page

Lost Circulation Continued

rock. As the mud flows into the fracture, it propagates the fracture and allows a loss of mud.

A great deal of progress has been made on preventing hydraulic fracturing by increased knowledge of formation pore pressure and fracture gradient. Advanced information on these two parameters allows the use of minimum mud weights and better casing programs. This is the first and most important method for preventing fracturing.

Lost circulation often occurs while circulating, while attempting to break circulation, or while running pipe in the hole. This is a result of the increase in total pressure exerted on the formation, due to the pressure required to move the mud up the annulus. The pressure due to the frictional drag of the moving mud stream is increased by increased flow rate or increased viscosity of the mud as it exists in the annulus. (**See Section II, "Pressure Control."**)

The highest mud viscosities in the annulus occur after a trip, due to "elation of the mud under static conditions at elevated temperature. Running the pipe into the hole under these conditions may cause excessively high pressure surges unless the peak pipe running speeds are carefully controlled. The running speeds should decrease with depth in the hole. In extreme circumstances, it may

Continued on next page

Lost Circulation Continued

be necessary to circulate out the gelled mud at one or more points in the hole before getting back to bottom. The mud should be treated to minimize downhole gelation before making a trip.

Returns are often lost while attempting to establish circulation after trips and on connections. If the hydrostatic pressure plus the pressure required to break the gel of the mud and initiate flow is greater than the fracture pressure, fracturing will occur. When the fracture pressure is known, the maximum allowable pressure to initiate circulation can be determined. With the use of a standpipe choke and pressure gauge, the pressure required to break circulation can be monitored and controlled. The pipe should be rotated a few minutes to break the gel structure of the mud as much as possible. Then with the choke open, start the pumps at idle speed while continuing to rotate the pipe. Slowly close the choke until the predetermined pressure is reached. If circulation is established, continue to close the choke in steps until fully closed. The standpipe pressure should never exceed a predetermined value at each circulation rate. The standpipe pressure should be monitored until after "bottoms up".

The pressure imposed on the hole while circulating can also be monitored and controlled by this method. A detailed procedure is given in **Appendix A**.

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Lost Circulation Continued

The usual remedy for an induced fracture is to wait 2 to 8 hours, or even as much as 24 hours, for the formation to heal. Also, reduce the mud weight if possible.

If the formation does not heal, the next step is to spot a mud pill (usually 50 barrels or more, depending on hole size) containing 10 to 50 lb./bbl of various sizes and types of lost circulation material. Bit nozzle sizes should be taken into consideration when selecting the concentration and type of lost circulation material to be used. Relatively coarse material should be used if possible, since its purpose is to bridge the fracture.

If the LCM in mud pill is not successful, some type of special high fluid-loss slurry with 30 to 50 lb./bbl of LCM is used to try to prop the fracture open and form a bridge to seal the fracture. A squeeze pressure equal to the final mud column weight is usually used. These slurries have met with varying degrees of success, but they usually do not have a lasting effect. However, these types of slurry will often seal the hole long enough to log or run and cement a string of casing. Some of the slurry recipes are shown in **Appendix F**.

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Lost Circulation

Continued

The types of lost circulation discussed thus far are those that occur in the open hole. Losses can also occur at the casing seat or through holes in the casing.

If mud is able to channel up behind the casing to a weaker zone, fracturing of this zone and loss of mud can occur. The usual procedure is to drill out 10 to 15 feet below surface or protective casing and test to a pressure approximately equal to the anticipated final equivalent circulating density. If the casing seal fails to hold, squeeze cementing is usually successful.

Subsequent testing in the open hole is also useful in determining the integrity of the hole. A pressure integrity test after opening the first sand below casing will indicate the highest mud weight that can be used without fracturing. When subsequent pressure integrity tests are run, it is not unusual for the "leak-off" pressures to increase. A good filter cake will strengthen the borehole. This may account for some lost circulation problems healing with time.

If a hole develops in the casing, mud can be lost to a lower pressure zone behind the casing. This type of lost circulation must be identified before taking remedial action. If the loss is assumed to be at the casing seat or in the open hole, and if a high water loss slurry or cement is spotted, it will move up the hole and stick the pipe. This

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Lost Circulation

Continued

possibility must be eliminated before attempting a cure for any lost returns problem.

Lost circulation problems vary from area to area, and no universal solution has been found. However, the following general rules should be kept in mind:

1. Drill with lightest weight mud practical.
2. Control mud properties to achieve lowest practical plastic viscosity, yield point, and gel strengths. Special emphasis should be placed on minimizing flocculation at downhole temperatures.
3. Control pipe running speeds to minimize surge pressures.
4. Use standpipe choke method to initiate circulation. Reduce circulating rates when necessary.
5. "Dry drill" where practical and where economics are favorable.
6. Avoid use of precautionary lost circulation material.
7. Do not use fine lost circulation materials. They do no more good than drilled solids and simply add to the viscosity of the mud.
8. Screen out coarse material as soon as possible after a batch treatment.

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Lost Circulation

Continued

9. Set protective pipe as deep as necessary to minimize lost circulation problems.
 10. Test casing seats to maximum mud weight anticipated.
 11. If returns are lost with mud weights 4 or 5 lb./gal higher than the formation pore pressure in which the last casing was set, a liner or casing string will generally be required.
 12. Locate the point of loss before spotting any type of pill that could set up around the pipe.
-

Pipe Sticking

Pipe sticking is one of the more costly drilling problems that we encounter. It occurs from any of these several different causes:

1. Differential pressure sticking.
 2. Accumulation of cutting or sloughings in the hole, due to inadequate hole cleaning.
 3. Plastic flow into the hole, such as salt.
 4. Key seats in crooked holes.
 5. Mechanical obstructions.
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Pipe Sticking

Continued

6. Sudden settling of barite, due to such things as barite stripping from gas flow or inversion of oil-mud emulsion.
7. Collapse of weak or unconsolidated formation, due to sudden reduction in hydrostatic head from lost circulation.

Obviously, the prevention or solutions of these various causes of stuck pipe are different and require correct identification before taking remedial action. Unfortunately, it is not always easy to identify the specific cause of pipe sticking and an incorrect assumption may lead to treatment which is detrimental. For instance, differential pressure sticking may be assumed when inadequate hole cleaning is the actual problem. If lignite and lignosulfonate are added to decrease the fluid loss and relieve the differential sticking problem, they will thin the mud and make the hole cleaning worse. Consequently, we must be careful not to jump to an incorrect conclusion and take action that will magnify the problem. Probably the best method of identification is by a process of elimination of all other possible causes.

Differential Pressure Sticking

The most prevalent form of pipe sticking is differential pressure sticking. It is the most significant problem related to the mud filter cake.

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**Differential
Pressure Sticking**
Continued

When the pipe becomes partially embedded in the filter cake, it becomes a part of the cake as though it were a mud solid. It is held to the cake by the pressure difference between the wellbore pressure and the pore pressure in the cake under the pipe. The force required to pull the pipe free is a function of the area of pipe in contact with the cake, the pressure holding it to the cake, and the coefficient of friction between the pipe and cake.

When the pipe first contacts the cake, the pore pressure at the surface of the cake is the same as the wellbore pressure and the pipe is free. As filtrate is squeezed from the cake, the pore pressure in the cake, which is under the pipe, decreases until it finally reaches formation pressure. This causes the differential pressure holding the pipe on the cake to increase to such a point that the resulting frictional drag exceeds available force to pull the pipe free.

Consequently, the time that the pipe is motionless is a very important controlling factor as to whether the pipe sticks to such a point that it cannot be pulled free.

The total differential pressure is usually imposed on the pipe in less than two hours. Often, only a few minutes is required for the pipe to stick to the point it cannot be pulled free. This makes it imperative that the pipe is kept in motion. Rotation of the pipe is best in that it continually pulls new mud between the cake and the pipe and prevents a buildup of the differential force.

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Differential Pressure Sticking

Continued

Since the differential force acting on the pipe increases from the time of initial contact until leak-off of the filtrate from the cake has allowed complete development of the differential pressure, some incidents of sticking may be eliminated if the rate of application of the differential force can be slowed. The rate of increase of the differential force is a function of the rate of flow of filtrate out of the cake. This is controlled by the cake permeability and thickness. Decreasing the permeability of the cake increases the time required to stick the pipe. Thus, a mud with a low fluid loss and low permeability cake is desired.

As a cake is being deposited, the filtration rate decreases as the cake grows thicker. This means that the rate of sticking is greatest during the early growth period of a cake. During a short trip, the cake may be scraped off and a new cake begins to deposit. The probability of sticking on this newly developing cake is greater than before. Extra care should be taken to keep the pipe moving.

The area of contact is a function of depth of burial of the pipe in the cake and, consequently, is a function of the cake thickness. For this reason, we want the cake to be as thin as possible. This means the cake should be of low permeability and deposited from a minimum-solids mud. For this purpose, there is no substitute for an adequate concentration of well-hydrated, dispersed bentonite. High solids

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Differential Pressure Sticking

Continued

content causes thick filter cakes. Drilled solids should be maintained at a minimum. Lignite, lignosulfonate, and other fluid-loss control agents reduce the cake permeability and the resulting cake thickness.

The coefficient of friction between the pipe and filter cake is largely controlled by the type of solids in the mud. Dry solids have a higher coefficient of friction than hydrated solids. Barite, sand, silt, and undispersed shale are dry solids that have coefficients of friction of approximately 0.4. Bentonite is a highly hydrated solid that forms filter cakes with a coefficient of friction of about 0.07. Obviously, it is desirable to maximize the amount of bentonite in a mud and minimize the amount of drilled solids.

As mud weight is increased the amount of barite in the mud is naturally increased, resulting in filter cakes with increased coefficient of friction. The cake thickness also tends to be greater due to the higher solids content. These two factors make it imperative that high-density muds carry a minimum amount of drilled solids and as much bentonite as possible, consistent with good flow properties. Also, the mud should be maintained in a deflocculated condition at bottom-hole temperature in order to minimize the high-temperature fluid loss.

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**Differential
Pressure Sticking**
Continued

Oil is often added to a mud to prevent sticking. It not only reduces the fluid loss but also decreases the coefficient of friction of the cake. Emulsified oil droplets are deformable under pressure and apparently spread, under the force of the pipe, against the cake and lubricate the interface. Diesel oil, although a poor lubricating oil, works quite well. Special additives can be added to diesel oil to improve its performance.

Oil must be well emulsified in order to function properly. This is usually not a great problem. Lignite added at the same time will aid in emulsification. For best results, the oil should be added slowly to the pump suction. From 3 to 5 percent oil is sufficient.

For environmental protection, several nontoxic substitutes for diesel oil have been placed on the market. These materials consist of alcohols, vegetable oils, specially refined mineral oil with low toxicity, surfactants, and other water-soluble lubricants. In general, they are very expensive and must be used in quite low concentrations. As a result, their performance does not compare to that of diesel.

The identification of differential pressure sticking is somewhat difficult. It occurs with little or no warning. The pipe is usually free of any undue torque or drag until it has been left motionless for a short period of time. If it is possible to pull the pipe free, it should be

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Differential Pressure Sticking Continued

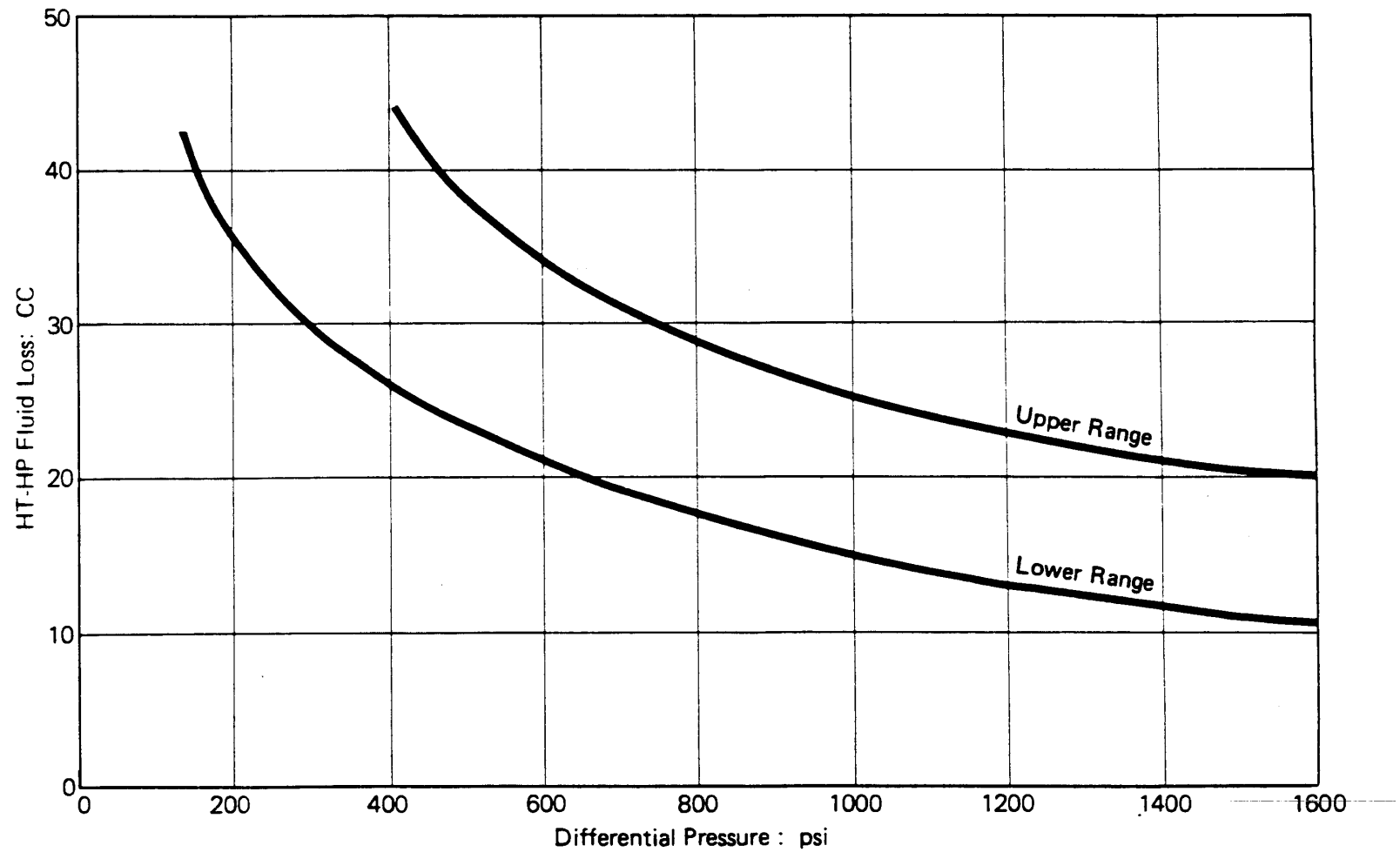
rotated as soon as possible in order to break the pressure seal with new mud being pulled across the face of the cake. It should be possible to circulate freely when the pipe is differential pressure stuck. This is in contrast to some of the other forms of sticking.

The existence of sands in the hole at pore pressures less than the hydrostatic pressure always makes differential pressure sticking a possibility. As the differential pressure overbalance on a sand is increased, extra care should be taken to avoid sticking the pipe.

Figure I shows a suggested range of HTHP fluid-loss values at various differential pressures. The location of these sands should be kept in mind. When at all possible, the drill collars should not be stopped for an appreciable period of time opposite such a sand, since the majority of pipe sticking occurs at the drill collars.

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Figure 1
Suggested Range of HT-HP Fluid Loss



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Differential Pressure Sticking

Continued

Many cases of differential pressure sticking occur while taking a kick. Obviously, this is a very critical time for sticking the pipe since increases in surface pressure on the annulus are directly translated to increased differential pressure. Often the pipe sticks due to being motionless after shutting in the well and before increasing the mud weight to kill the well. Moving the pipe as much as possible after shutting in the well would prevent some cases of sticking. The pipe should periodically be rotated slowly and reciprocated. Care should be taken to avoid excessive wear at one point on the pipe.

When the pipe has become stuck, one of the first steps to free the pipe is to spot oil or oil mud over the stuck interval. The oil apparently compresses the cake away from the pipe and penetrates between the pipe and cake. In this manner, the stuck area is gradually decreased until the pipe can be pulled free.

The time required for freeing the pipe may range from 1 to 48 hours. There have been cases where the pipe came free after 72 hours; however, the probability of getting loose after 48 hours is very small.

One of the most prevalent causes of failure to free the pipe is because the oil was not spotted over the entire stuck interval. Hole enlargement can cause considerably larger volumes of spotting fluid to be required than the calculated hole volume. This should be taken into account when sizing the volume of spot to be used. If possible,

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Differential Pressure Sticking

Continued

the entire open hole should be filled with the spotting fluid. Sufficient spotting fluid should be left in the pipe to allow pumping 1 to 3 barrels every hour while the soaking procedure is in progress.

Wetting agents added to the oil sometimes appear to speed the soaking process. If the differential pressure can safely be reduced, this will also aid in freeing the pipe.

When the spotting procedure fails to free the pipe, the next step is usually a complete displacement of the system with an oil mud. This accomplishes two purposes. First, a more complete removal of the water base mud from around the pipe may be accomplished by circulating an oil mud. If this occurs, the pipe may be freed. Secondly, an oil mud reduces the possibility of sticking the washpipe on a washover operation if this course of action is taken.

Pipe Sticking Due to Poor Hole Cleaning

When cuttings and sloughings accumulate in the hole, they cause excessive torque and drag and possibly eventual sticking of the drill string. This is essentially a result of inadequate hole cleaning, and is usually associated with borehole instability.

When a shale begins to slough, hole enlargement occurs. The annular velocity in the enlarged section decreases and eventually reaches the point where the larger pieces of rock can no longer be

Continued on next page

**Pipe Sticking Due
to Poor Hole
Cleaning**
Continued

lifted. They can accumulate in the washed-out section and fall in the hole when circulation is stopped or when they are dislodged by pipe movement.

When sloughing is occurring and the hole is washed out, special effort should be placed on insuring adequate hole cleaning. There are several indicators of hole-cleaning difficulty which should be watched.

The conditions of cuttings and sloughing coming across the shaker should be checked. If the edges of the larger pieces are rounded, it indicates they have been tumbled in the hole and are not being lifted efficiently. The amount of shale coming across the shaker may tell you how badly the hole is sloughing, but it is not a good indicator of how much is being left in the hole. Severe problems can occur even though there are no clear-cut indications from the amount or appearance of the shale being carried to the surface.

The occurrences of increased torque or drag are normally the first indications of hole problems due to inadequate cleaning. This condition will normally persist, appearing to move down the hole as drilling progresses, and it will grow in severity. Sometimes, sudden increases in pump pressure will be observed as bridges form and obstruct the flow of mud up the annulus.

Continued on next page

**Pipe Sticking Due
to Poor Hole
Cleaning**
Continued

Sometimes a trip can be made without difficulty, but bridges and fill will be encountered when going back into the hole. This is a positive indication of inadequate hole cleaning that may lead to stuck pipe on the next trip. However, the absence of fill does not eliminate the possibility of trouble, because the accumulation may be up the hole in a washed-out section.

During a trip the first stand or two may pull free, then begin to drag as the shale falls in around the pipe. The drag will usually persist until the bit has cleared the point of accumulation. If the drag suddenly begins to increase as though the shale is packing around the pipe, the pipe should be stopped, the kelly connected, and an attempt made to establish circulation. If circulation cannot be established, an attempt should be made to work the pipe down to loosen the bridge, then establish circulation. If it is possible to free the pipe in this manner, it may be necessary to pump out singles until the obstruction is cleared.

When it is apparent that the hole is not being cleaned, the yield point of the mud should be increased. The amount of increase required is unknown because the sizes of the pieces of rock to be lifted are unknown. Some threshold level of lifting capability is required for each size, which increases as the size of the rock increases. The

Continued on next page

**Pipe Sticking Due
to Poor Hole
Cleaning**
Continued

hole will not clean up until this threshold level is reached. In general, the yield point may need to be increased from 2 to 4 times the normal value.

The lifting ability of a mud increases as mud weight increases, since the buoyed weight of the particle decreases. The weight of a piece of rock in a 15 lb./gal mud is only about half of its weight in a 10 lb./gal mud. Consequently, the yield point required in a 15 lb./gal mud is only about half that of a 10 lb./gal mud.

An alternate method for increasing the lifting capacity is to increase the pump rate. This should be done with caution since it may lead to increased sloughing or lost returns. It probably has application only when the present pump rate is abnormally low.

When water is used as the drilling fluid, viscous pills can be circulated periodically to sweep the hole. This approach has limited success. In some cases the duration of the sweeps is not sufficient to unload the hole. Also, it does not have the added protective feature of being left in the hole to "gel up" and immobilize rubble in washed-out sections of the hole.

There are a number of methods for increasing the yield point of a mud. It should be done in such a way that the plastic viscosity is not

Continued on next page

**Pipe Sticking Due
to Poor Hole
Cleaning**
Continued

appreciably increased. Increasing the plastic viscosity is a very inefficient way to increase the lifting capacity and causes decreased penetration rates.

We are interested in increasing the yield point at the temperatures that exist downhole. The yield point of polymer muds decreases with increased temperature. Polymers are also susceptible to thermal degradation at temperatures above 225°F. For these reasons, polymers should not be used to increase the yield point at higher temperatures. Hole-cleaning problems often occur when using polymer muds even when the yield point at the surface appears to be adequate.

Addition of bentonite is a quite efficient method for increasing the yield point. This is especially true when it is allowed to flocculate. Thinners should not be used when attempting to increase the yield point. In light-weight muds, flocculation can be promoted by addition of lime or soda ash. This causes high yield points to be developed with low plastic viscosity and allows for both good hole cleaning and fast penetration rates.

Pipe Sticking Due to Plastic Flow of Salt

Salt will flow as a plastic when subjected to high differential stress and high temperature. In a well, the differential stress is the difference in overburden pressure and mud pressure. It increases with depth unless compensated by increased mud weight.

Temperature also increases with depth. Consequently, when salt is encountered deep and hot, increased mud weight is required to prevent sticking of the bit and bottom-hole-assembly due to salt movement.

Figure 2 shows mud weights for various depths and temperatures required to limit salt flow to 0.1 percent area closure per hour. Experience has shown that these mud weights are good estimates of the mud weights required to prevent sticking when drilling with an oil mud or salt saturated mud which will not dissolve salt.

If a water base mud that is not saturated with salt is used, some dissolving of the salt will occur. This will tend to reduce the rate of closure and in some cases may allow use of mud weights somewhat less than indicated in the figure. The rate at which the mud will dissolve the salt decreases as its salinity increases. Large amounts of dilution may be required to maintain reduced salinity and high dissolving rates if a thick section of salt is drilled.

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Pipe Sticking Due to Plastic Flow of Salt

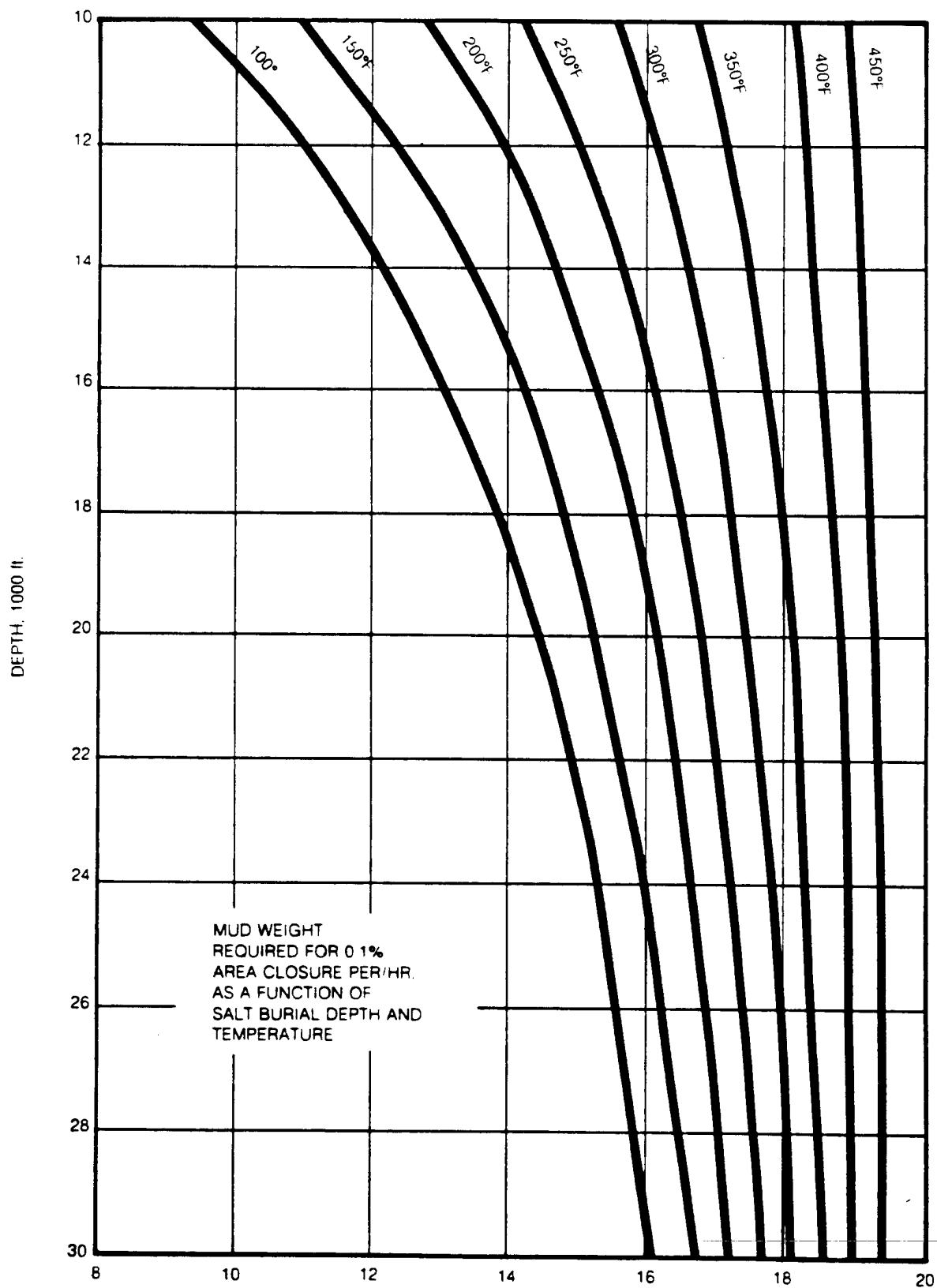
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The temperature of the salt is probably more critical than any other factor in causing salt flow. At very high temperatures the rate of salt movement is too great to be completely counteracted by leaching if significantly reduced mud weights are used.

When sticking due to salt flow occurs, fresh water should be spotted over the stuck interval. Some of the water should be left in the pipe so that the water over the stuck interval can be replaced periodically to maximize the dissolving rate.

Mud Weight, Lb./Gal.

Figure 2



MUD WEIGHT
REQUIRED FOR 0.1%
AREA CLOSURE PER/HR.
AS A FUNCTION OF
SALT BURIAL DEPTH AND
TEMPERATURE

Mud Weight, Lb./Gal.

Figure 2

Section VI

SOLIDS CONTROL

Solids Control

Solids control is the most important function in mud treating. Control of mud properties centers around the treatment necessary to counteract the continual influx of drilled solids into the active mud system. Almost all of the costs of treating a mud can be directly attributed to solids control.

Undesirable solids increase drilling costs in a number of ways in addition to increased mud costs. If not properly controlled, they lead directly to such problems as lost circulation, differential pressure sticking, and reduced penetration rate.

There are basically three mechanisms for reducing the solids content of a drilling fluid. These are dilution, screening, and settling or centrifuging. Dilution is accomplished by adding liquid to reduce the concentration of solids in a given volume. Solids can also be reduced by passing the mud over a screen and discarding those particles that will not pass through the screen openings. Solids can be separated from a fluid by settling or by imposed centrifugal force. This is accomplished in settling pits, hydrocyclones, and centrifuges.

Continued on next page

Solids Control

Continued

All these methods are used and have a place in mud treating. However, the method that will work best and most economically is a function of mud type, density, viscosity, and cost. The degree of solids control necessary is a function of the severity of the drilling problems, and the type of formation being drilled. This will also influence the method of solids control that should be employed.

Our basic aim in solids control is to reduce the formation solids content of a mud to a practical limit that will allow us to maintain the filtration and flow properties in a range to best handle all of the drilling problems. This means that we must pay special attention to control of the particles less than 2 microns in size, since they are dominant in determining the mud properties. Unfortunately, the small particles are the most difficult to remove. To reduce the concentration of these particles, it is necessary to either dilute and build mud volume or to centrifuge the mud. When centrifuging, these small particles are discarded along with a portion of the liquid phase which contains a large portion of the chemicals in the mud. Both dilution and centrifuging are expensive. Centrifuging is normally considered to be less costly in muds weights above 12 lb./gal.

The problems and cost of removing the small particles makes it imperative that we remove as much of the large particles as possible before they are reduced to the fine size range. This is accomplished

Continued on next page

Solids Control

Continued

primarily by screening weighted muds and by using desanders and desilters on unweighted muds. The cost of controlling solids goes up as the mud density increases.

The cost of reducing the solids content in a 10 lb./gal mud is approximately half that of a 12 lb./gal mud and one-fourth that of 17 lb./gal mud. This means that we should begin weighting up a mud which contains a minimum amount of drilled solids. This will insure a minimum cost and better mud properties at all times.

Dilution

The addition of water to a mud system directly results in the cost of converting that water into mud of the proper density and chemical content. The volume of new mud which is built increases the total volume of the mud system, thereby reducing the concentration of drilled solids in the mud.

The first rule for minimum dilution cost is to maintain the mud system at minimum volume. A volume of mud equal to the volume of new mud to be built should be removed from the mud system prior to beginning dilution. This results in a maximum percent dilution from the addition of a given volume of new mud. The mud discarded prior to dilution is also of less value than the mud discarded after dilution, because it contains more of the undesirable solids.

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Dilution

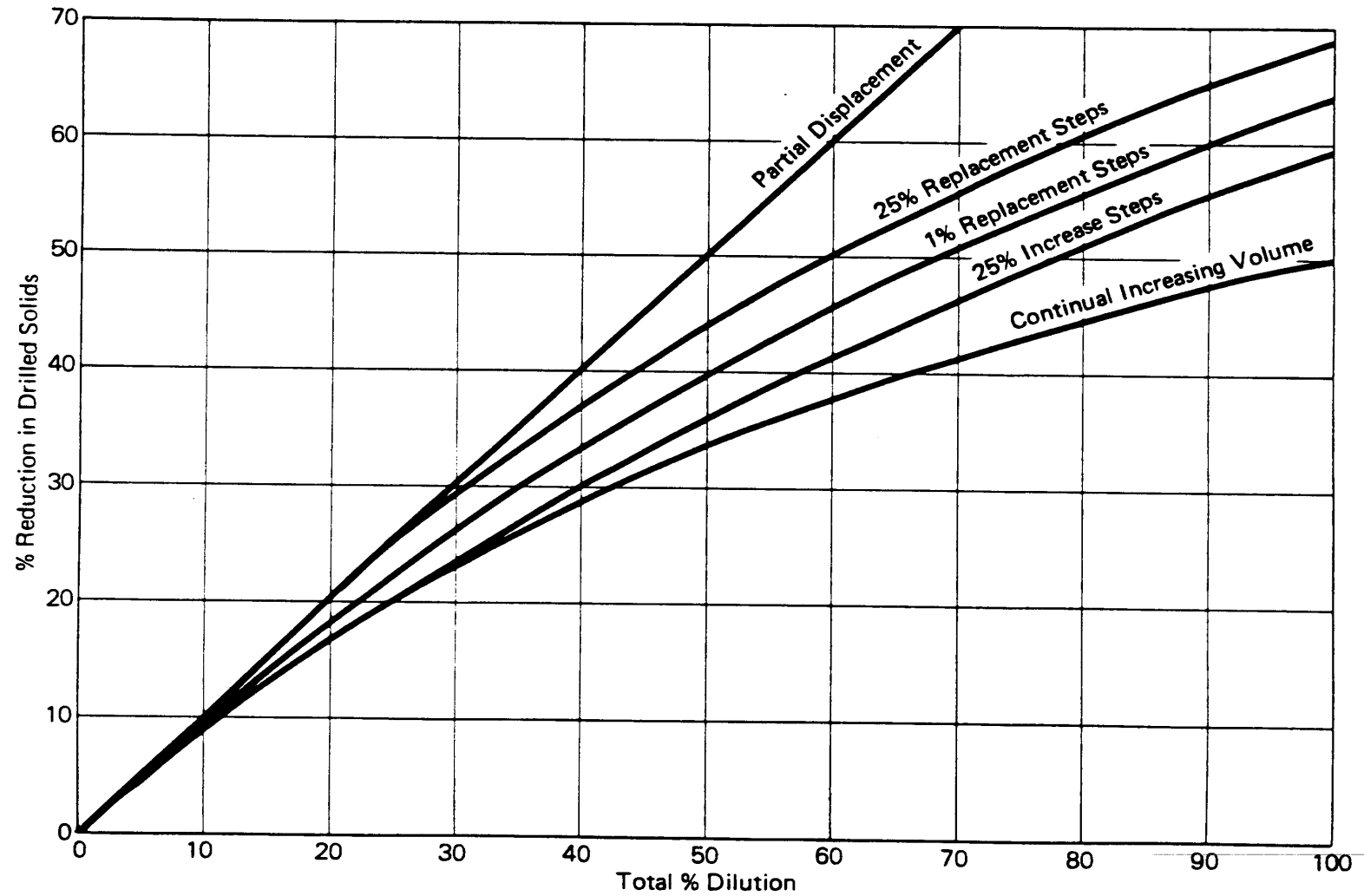
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This leads to rule number two. The mud should be diluted to the desired solids content in one step rather than a series of smaller steps. The mud discarded at each step contains some of the new mud from the previous dilution. Consequently, the total cost to reduce the solids content to a predetermined level will be considerably more if done in small stages than by a single dilution or displacement of part of the mud system.

These conclusions are illustrated in **Figure 1**. Consider the situation where it is desired to reduce the drilled solids content by 50 percent. The least expensive way to accomplish this is to discard half the mud system and replace with new mud. If the system is diluted by a series of discard-and-replace steps, the required dilution volume and cost will increase as the size of replacement steps decreases.

Continued on next page

Figure 1
Methods of Dilution



Dilution

Continued

If the mud system is allowed to increase in volume, the costs will be even higher. If the system is allowed to increase in volume by 25 percent and then discarded back to original volume, the cost will be 76 percent higher than partial displacement cost. The most expensive dilution method is to allow the volume to continually increase. This will result in twice the cost of a partial displacement to reduce the drilled solids content by 50 percent.

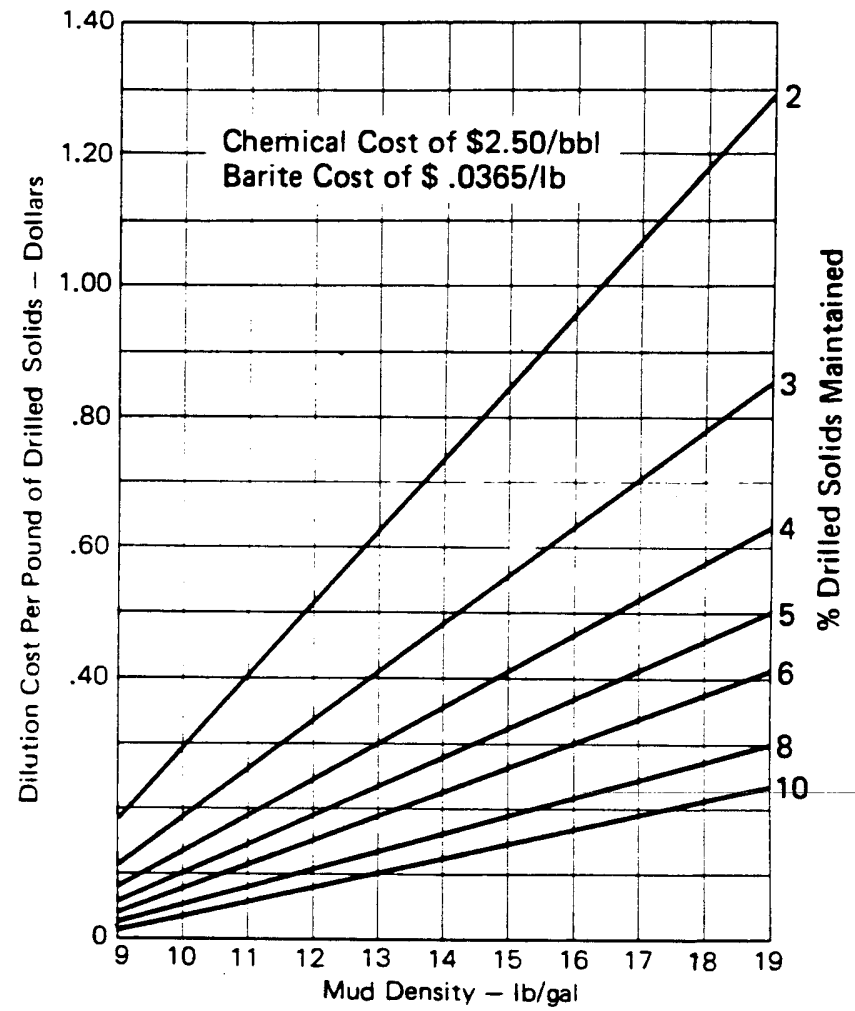
Obviously, the expense of dilution can be minimized by proper application of these principles. The dilution program should be planned rather than left to chance. The solids content can be allowed to build during intervals where careful control is not necessary and then reduced by massive dilution before proceeding into more critical situations.

The cost of controlling solids by dilution is a function of mud weight and the amount of drilled solids incorporated into each barrel of mud. **Figure 2** illustrates the dilution cost per pound of drilled solids as a function of mud weight and volume percent drilled solids carried in the mud. For the purpose of this figure, the bentonite and chemical costs were assumed to be \$2.50/bbl at all mud weights and a barite cost of \$.0365/lb.

As the mud weight increases and the amount of drilled solids allowed to incorporate in the mud decreases, the cost of controlling

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Figure 2
Cost of Dilution



Dilution

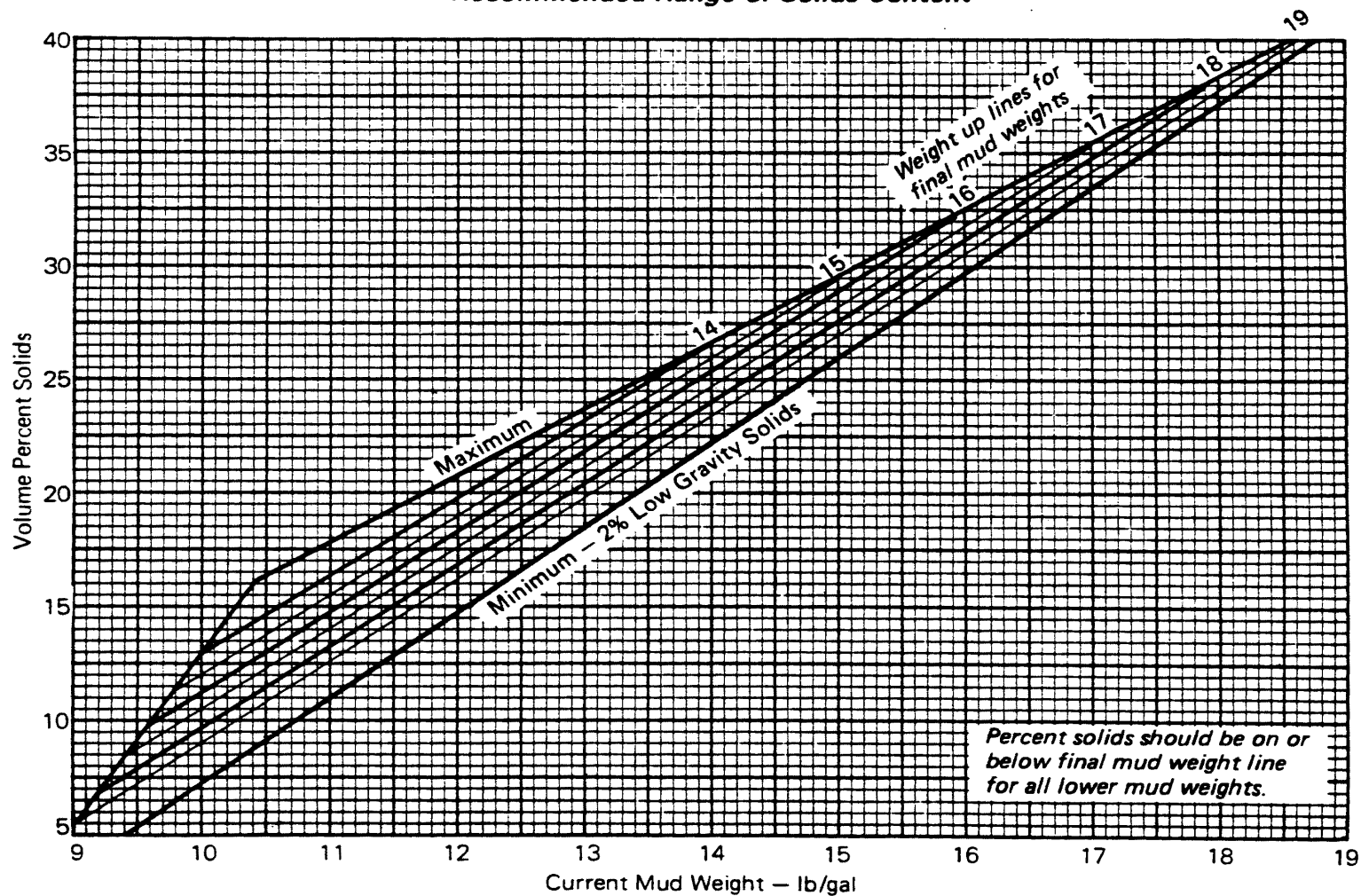
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the drilled solids concentration increases. In other words, as mud weight increases, the cost of a barrel of new mud increases; and as the allowable concentration of drilled solids in the mud is decreased, the barrels of new mud required to maintain a given percent drilled solids increases. This gives us two more methods for reducing dilution costs. First, dilute the mud and reduce the drilled solids content at low mud weights rather than waiting until the mud weight has been increased and it becomes necessary to dilute in order to achieve the desired properties. This is simply a matter of planning ahead. If the mud contains more drilled solids at the low mud weight than can be tolerated at the highest expected mud weight, the solids should be reduced at this time to a level that will allow increasing the mud weight without subsequent dilution.

Figure 3 may be used as a guide to the solids content at each mud weight that will allow increasing the mud weight to the highest expected value without further dilution. For example, if the current mud weight is 10 lb./gal and the highest expected mud weight is 16 lb./gal, the 10 lb./gal mud should contain no more than 11 volume percent solids. To allow for future incorporation of drilled solids, it would be well if the mud contained considerably less than 11 percent solids. At each mud weight along the way, adjustments in the solids content can be made as necessary.

Continued on next page

Figure 3
Recommended Range of Solids Content



Dilution

Continued

When the solids content increases with increased density more than predicted by this chart. it indicates that solids removal is not keeping pace with the solids influx. This signals a need for more solids removal capability by such means as finer screens or more centrifuging.

The other factor controlling dilution cost is the percent drilled solids that we allow the mud to contain. Obviously. the mud maintenance cost is reduced if higher drilled solids concentrations are allowed. However, the problems that high concentrations of drilled solids cause often far outweigh any savings in mud costs. Our first concern should be to control the solids to such a point that we can achieve and maintain the required mud properties.

The solids content outlined in a mud program should be realistic. If it is lower than needed. the mud maintenance costs will be forced to be higher than necessary. If it is not consistent with other designated mud properties it will lead to confusion.

Screening

In an average day of drilling, several tons of drilled solids are carried to the surface by the mud. If all of these solids were incorporated in the mud, several hundred barrels of dilution would be required to maintain the mud properties. Obviously, some form of mechanical removal of these solids is necessary.

Continued on next page

Screening

Continued

Since screening is a relatively low-cost process that does not waste any appreciable amount of barite or chemical, it is the most desirable means of solids control. In essence, the only cost of screening a mud is the rental cost of the equipment and replacement of screens.

Effort should be made to maximize the amount of drilled solids removed by screening. This means that 100 percent of the mud stream should be screened at all times through as fine a screen as possible without screening out an excessive amount of barite. API specifications on barite call for a maximum of 3 percent barite retained on a 200-mesh screen. This means that screens approaching 200 mesh can be used without wasting an excessive amount of barite.

A woven wire cloth made from stainless steel is normally used for mud screening on shakers. This wire cloth is usually specified by mesh. The mesh is the number of openings per linear inch. Unfortunately, the mesh designation is not sufficient to describe the screen. The wire size which is used also influences the opening size and the percent open area of the screen. The finer the wire diameter the greater will be the screen capacity. However, screen life will be less and the opening size greater -- both of which are undesirable. There must be a compromise between opening size, capacity, and screen life.

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Screening

Continued

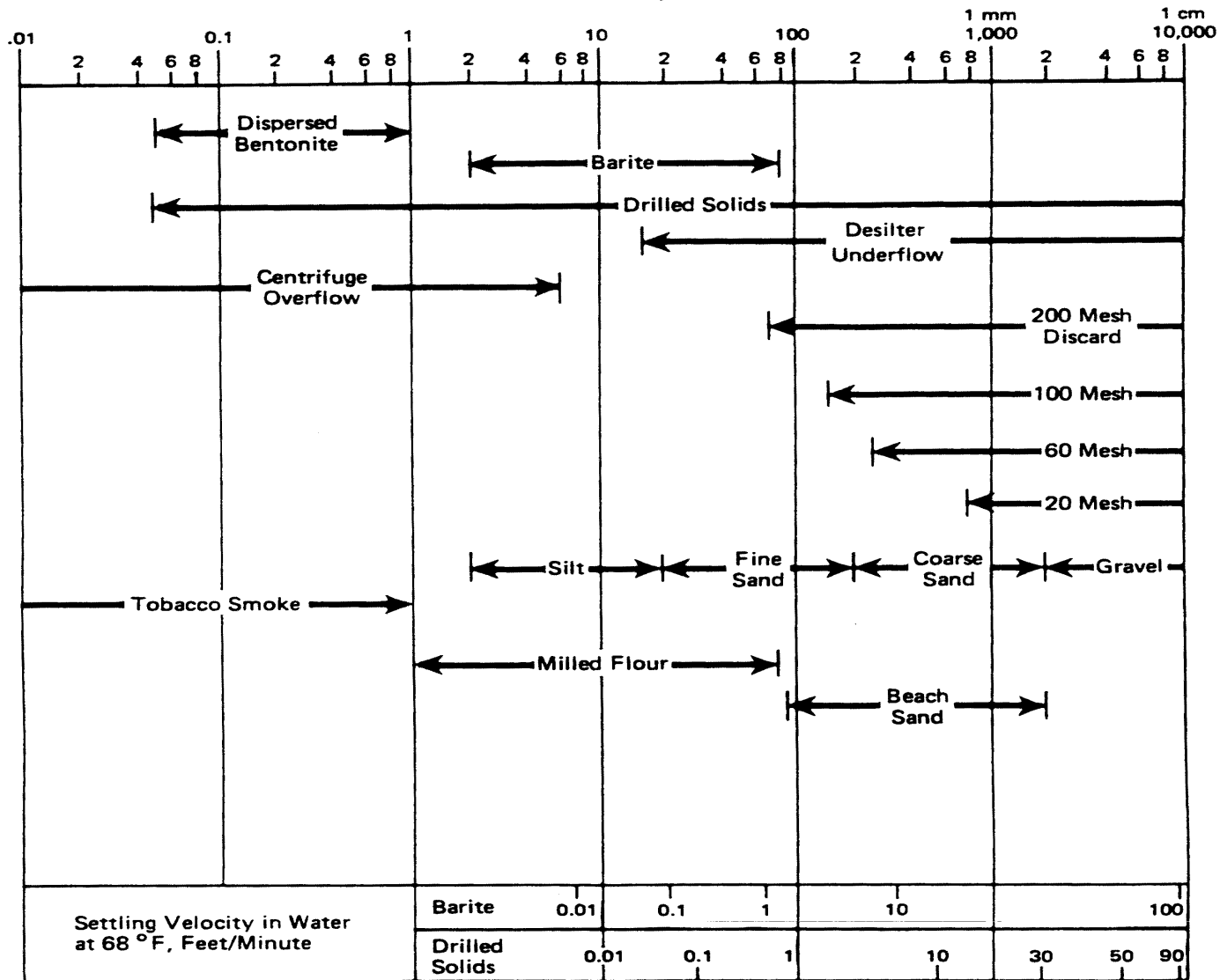
Screen designations have also been complicated by screens which have rectangular rather than square openings. Such a screen may have 80 openings per inch in One direction and 40 in the other direction. This screen would be specified as an 80 x 40 mesh screen. Obviously, it would have a greater capacity than a square 80 mesh, but would allow some particles to pass that would be retained on a square 80 mesh.

Much confusion has resulted from insufficient screen description. Through indiscriminate use of the term “equivalent”, screens have been represented as one size when they are actually something else. To properly describe a screen, the mesh and opening size in both directions and the percent open area are needed.

Particle sizes and screen openings are usually measured in microns. A micron is 1/1000 of a millimeter, or 0.0000394 inch. **Figure 4** shows the size ranges of various types of particles and the size ranges removed by different screens and solids-control equipment.

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Figure 4
Particle Diameter, Microns



Screening Continued

Drilled solids may exist in the mud system in any size ranging from the finest dispersed bentonite, 0.05 microns, up to the largest cutting or sloughing. The purpose of screening is to remove as much as possible of the drilled solids larger than the barite particles. In this manner bentonite, barite, and the liquid phase of the mud containing the chemicals are salvaged; the coarse, drilled solids are discarded. Since only a very small amount of mud that adheres to these larger particles is lost from the system, screening is a very economical way to remove drilled solids.

The drilled solids normally reduce in size with time and continued circulation in the mud system. When they enter the barite size range, it becomes impossible to separate them from the barite until they are further reduced in size and become smaller than the barite particles. At this time a centrifuge can be used to separate a portion of the liquid fraction of the mud containing these small particles along with the chemical and bentonite. This operation is expensive and removes only a small fraction of the total drilled solids. This makes it imperative that we remove as much of the drilled solids as possible the first time they reach the surface.

For many years, shakers did not exist that would handle the high-volume requirements with fine screens. Conventional shakers were generally equipped with 12 to 20 mesh screens. This allowed all

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Screening

Continued

particles less than about 840 microns to become incorporated in the mud and caused dilution to be necessary to control the mud properties.

Recent improvements in shale shakers allow the use of much finer screens than is possible with the conventional shakers. These new shakers are normally somewhat larger and operate at a higher vibrational frequency than conventional shakers. Some are designed so that the speed and amplitude can be easily changed to fit the needs of various muds. Under normal conditions they will handle about 400 gal/min of mud with an 80-mesh, 178-micron, screen. Figure 5 shows the opening size, wire diameter, and percent open area for a number of different screens representative of those most commonly used on shakers. These specifications may vary somewhat, depending on the manufacturer, but should serve as a guide.

Increased mud viscosity will reduce screen capacity. As a rule, the capacity will be reduced about 2 percent for every 10 percent increase in viscosity. Often, it is necessary to start with coarse screens and change to finer screens as the flow rate is decreased or the drilled solids content is reduced. Where flow rates are low, it has sometimes been possible to screen high-weight muds with two shakers using screens as fine as 200 mesh.

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Figure 5
Representative Shaker Screen Descriptions

	Opening Size		Wire Dia.	Percent
Mesh	Microns	Inches	Inches	Open Area
10	1905	0.075	0.025	56.3
20	838	.033	.017	43.6
40	381	.015	.010	36.0
60	234	.0092	.0075	30.5
80	178	.007	.0055	31.4
100	140	.0055	.0045	30.3
120	117	.0046	.0037	30.9
160	97	.0038	.0025	37.64
200	74	.0029	.0021	33.6

Screening
Continued

Careful attention should be given to maintaining the shaker in good working condition and insure that the finest screens that will handle the entire mud stream are used at all times. Every pound of solids that is missed by the shaker will cost several times as much to be treated or removed from the mud system by another means.

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Screening

Continued

If the pounds of drilled solids removed by the shaker per day can be estimated, this number divided into the shaker rental and screen replacement costs will give the cost per pound of solids removed. This cost can then be compared to an estimated dilution cost found on Figure 2. A comparison of these two numbers will indicate the advantage derived from the shaker. In most situations, the shaker costs will be less than dilution costs from spud to total depth.

Muds that retard dispersion or lift the cuttings out of the hole in a minimum length of time also aid screening efficiency. This insures that the particles remain as large as possible, thus allowing the maximum amount to be removed by screening. Oil muds are particularly good at inhibiting dispersion of shale particles. Normally, a fine-screen shaker will control buildup of drilled solids content in an oil mud with only a minimum amount of dilution being necessary.

Settling

Solids can also be separated by taking advantage of the fact that solids of different sizes and densities settle at different rates. The settling velocity of a particle increases as a function of increased gravitational force, increased particle diameter, increased difference in density of particle and fluid, and decreased fluid viscosity. The exact functions of these variables depend on particle size, rate of settling, shear behavior of the fluid, and interparticle interference.

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Settling

Continued

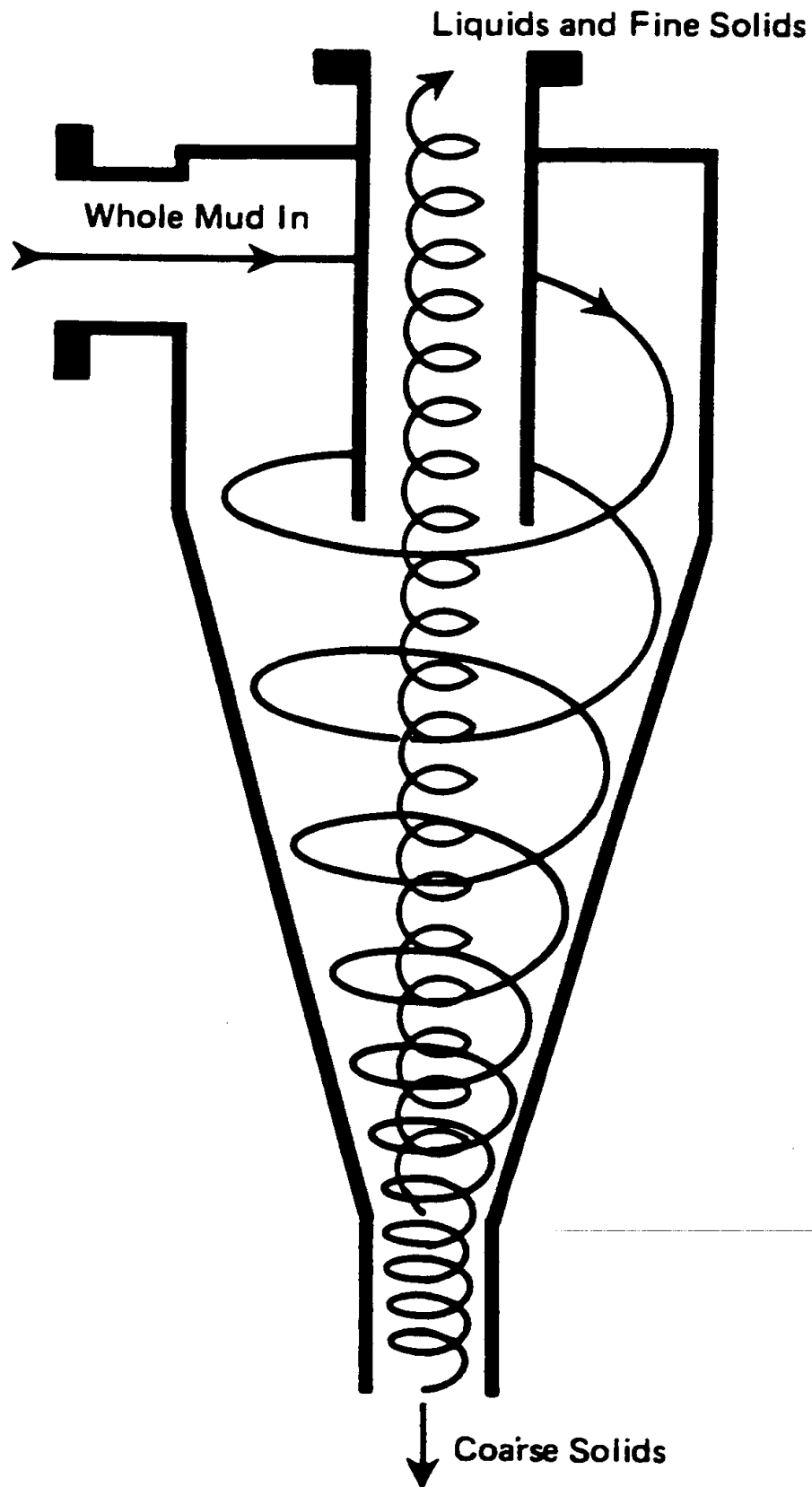
Unfortunately, there is no single equation that can be used to calculate settling rates under all conditions.

Settling pits were the first attempt to separate drilled solids from a mud. When the mud was allowed to stand quiescent in the pit for a period of time, the larger solids settled to the bottom. Mud with a lower solids concentration could then be skimmed from the top of the pit. This procedure has a number of shortcomings. Large surface volumes are required in order to allow the necessary time for settling to occur. Only the quite large particles will settle in a practical length of time. As mud weight increases, the settling times become greater; development of gel strength will completely stop the settling of all particles too small to overcome it.

In practice, settling pits are almost completely worthless except when drilling with clear water. Even in this case, flocculants are sometimes needed to aggregate particles into a larger size that will settle faster.

To overcome these deficiencies, devices such as centrifuges and hydrocyclones were built. These devices increase the gravitational force acting on the particles, thus increasing the rate of settling.

Figure 6
Hydrocyclone



Solids Control

Hydrocyclones

Hydrocyclones are a broad classification of settling devices that includes the desilter, desander, and clayjector. These are all basically the same device in different sizes which separate solids at different cut points. A cross-sectional diagram of a cyclone is shown in **Figure 6**. The mud is pumped into the cyclone through a tangential opening at the large end of the cyclone. This results in a rotating motion of the fluid, much like a water spout. The resulting centrifugal force causes the particles to concentrate at the wall. The dense layer next to the wall travels downward and is ejected at the bottom of the cone. The remainder of the mud travels upward and exits through the overflow end.

At the overflow end, a short pipe called the vortex finder extends down into the hydrocyclone past the mud intake. It keeps mud from short-circuiting directly to the overflow. In effect, it taps the light portion of mud in the cyclone, allowing only the dense sludge to spiral down to the underflow. If mud is fed to the cyclone at too high a pressure, some of the mud will exit the overflow without having time for the solids to segregate. If the feed pressure is too low, poor separation of solids occurs. This makes it imperative that the hydrocyclone be operated at the manufacturer's recommended pressure. Four-inch desilters are generally designed to operate at 40-45 psi, and six-inch desanders at 35-40 psi.

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Hydrocyclones

Continued

The cut point of a solids-separation device is usually defined as the particle size at which half of the particles go to the underflow and half to the overflow. In general, the cut point is reduced as the hydrocyclone diameter is reduced. Six-inch cyclones are rated at 30-35 microns cut point, 4-inch at 15-20 microns, and 2-inch at 5-10 microns. These cut point ratings are based on measurements taken on minimum-viscosity suspensions at optimum operating conditions. As a result, they are lower than will actually be attained on field muds.

For maximum removal efficiency, the underflow discharge should be in the form of a spray. A rope-shaped discharge means that some of the solids which should come out in the underflow are forced to go to the overflow.

The removal efficiency is also a function of the viscosity and density of the mud. Since the settling rate of a particle is decreased by increased viscosity and density of the mud, the percent of particles of any given size which reach the underflow is decreased. In other words, an increasing amount of the larger particles go to the overflow and are returned to the mud system. This means that desilting should be started before the drilled solids build up in a mud and increase the viscosity and density.

Solids that are not removed from the system at the first opportunity tend to be reduced in size as they are re-circulated. As they reduce

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Hydrocyclones

Continued

in size, they not only become too small to be removed by a desilter, but they also quickly build viscosity which reduces the efficiency of the desilter in removing the larger particles. For these reasons, the desilter should be considered as a means of preventing solids buildup rather than a means of reducing solids content.

When water is being added to the mud, it should be added upstream from the desilter in order to reduce the mud viscosity and improve the efficiency of the desilter. Addition of chemical, bentonite, or other mud additives should be added to the system downstream from the desilter so that none is discarded by the desilter.

Desanders or fine-screen shakers should be used ahead of the desilters in order to remove the larger particles that can clog or overload the desilter. Clogged discharge on the underflow of a cyclone probably accounts for more inefficient desilter performance than all other problems.

The desilter unit should be sized to handle 125 to 150 percent of the mud circulating rate. Each hydrocyclone will process from 50 to 75 gal/min. The suction, feed, and overflow lines should be sized with generous diameters and minimum lengths in accordance with good centrifugal pump installation practices.

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Hydrocyclones

Continued

When operated in the conventional manner, a large fraction of the particles in the barite size range are discarded by desanders and desilters. It follows that large quantities of barite will be discarded when these devices are used on weighted muds. Normally, this will cause prohibitive costs of mud maintenance. In general, the desander and desilter should only be used on unweighted muds.

A procedure for determining the pounds of solids removed per hour and the cost of removal is given in **Appendix B**.

Desilter-Screen Combination (Mud Cleaner)

Since the use of a desilter on a weighted mud is prohibitively expensive (due to loss of barite), and since ultra-fine screens are incapable of handling the entire mud stream, another type of solids removal device is necessary. A unit consisting of both of these devices eliminates their individual limitations.

If a mud is desilted, the underflow will contain a fraction of the barite in the mud as well as undesirable solids. However, an ultra-fine screen shaker has the capacity to handle the reduced volume of the underflow. If screens with openings slightly larger than the largest barite particles are used, only the drilled solids will be retained on the screen. The remainder of the underflow containing the liquid and barite can be returned to the mud system along with the desilter

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**Desilter-Screen
Combination (Mud
Cleaner)**

Continued

overflow. The net result is to be able to desilt a mud without losing an excessive amount of barite.

The solids removal efficiency of this unit depends on the efficiency of the desilter. Any particle that escapes to the overflow is returned to the mud system. For this reason, it is possible for particles larger than the screen openings to be retained in the mud system if they are not separated to the underflow of the desilter. This makes it imperative that the desilter be operated in the most efficient manner.

Since the efficiency of a desilter is reduced by increased viscosity and density of the mud, this unit will lose efficiency as mud density increases. However, this is not to say that its efficiency will necessarily be reduced below that of alternate means of controlling the solids.

It is best suited for the low-to-intermediate weight range of 10-15 lb./gal. This is fortunate, since the centrifuge becomes less efficient when compared with dilution in the low mud weight range. The mud cleaner should be started at the beginning of weightup and continued as long as the rate of drilled solids removal will justify the rental cost.

A screen size of 120 to 160 mesh is recommended for this unit. This will remove solids larger than about 100 microns without removing

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Desilter-Screen Combination (Mud Cleaner)

Continued

much of the barite. Screens of 200 to 250 mesh have been used. However, barite consumption increased substantially.

The unit should be shut off for one or two circulation cycles when adding barite. Otherwise, considerable amounts of the newly added barite will be removed from the system. It appears to take this long for the barite to become dispersed in the mud.

In screening, desilting, or use of this combination unit, only the coarser particles are removed. Particles that enter the mud system in a finer size are not removed by these devices and continue to build in concentration. Although the buildup of these solids is slower than if the larger solids were also left in the system and allowed to break up and disperse, some type of control will eventually be necessary. In weighted mud, the use of a centrifuge will usually be required to remove the colloidal-size particles, which have the most pronounced effect on mud properties.

Centrifuge

The mud centrifuge which is also a settling device is designed to remove small, drilled particles while saving barite. It consists of a conveyor screw inside a cone-shaped bowl that is rotated at approximately 1600 to 1800 rpm. The conveyor screw rotates in the same direction as the bowl but 20-40 rpm slower. Figure 7 indicates how the decanting centrifuge works.

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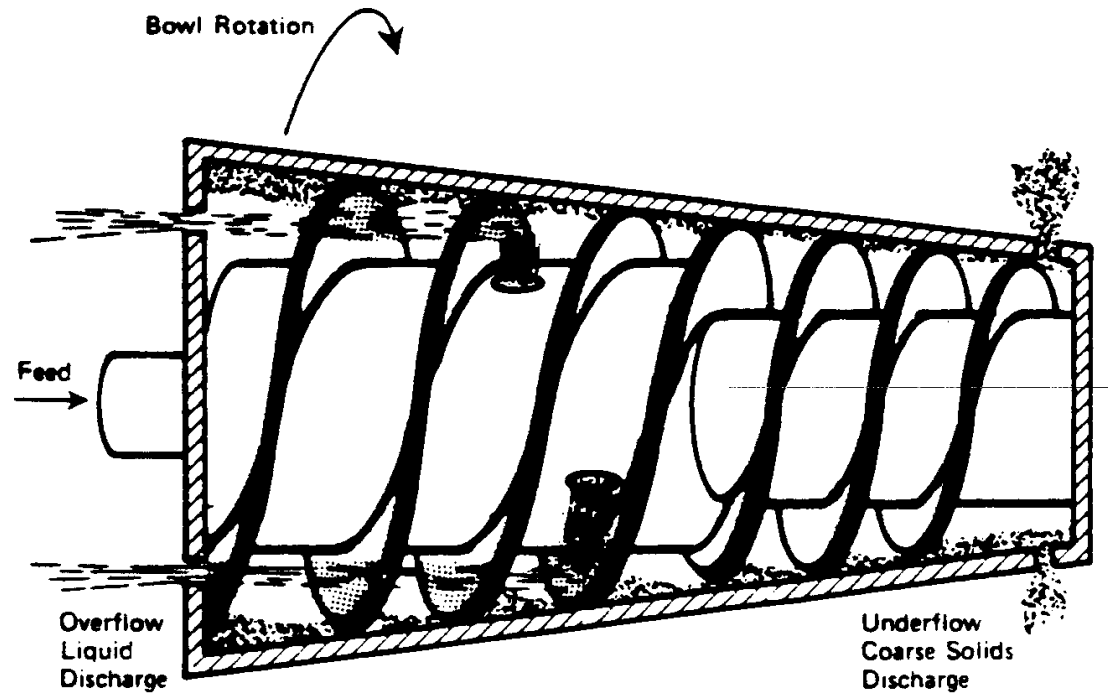
Centrifuge

Continued

Mud with dilution water is metered into the centrifuge through the hollow shaft in the conveyor screw. The mud is thrown to the wall of the bowl by the centrifugal force of rotation where it forms a pool. A circular row of ports at the large end of the bowl allows the liquid portion of the mud at the top surface of the pool to flow from the centrifuge. As the mud moves toward these overflow ports, solids settle toward the wall, where they are scraped by the conveyor screw toward the underflow ports at the small end of the bowl. In this manner the mud is divided into two streams, the light overflow, which weighs approximately 9.5 lb./gal, and the heavy, concentrated underflow slurry, which weighs approximately 23 lb./gal.

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Figure 7
Schematic of Decanting Centrifuge



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Centrifuge Continued

The primary factors that determine the minimum size of the particles which will settle to the wall and be discharged at the underflow are:

1. Bowl speed (centrifugal force)
2. Mud viscosity
3. Mud feed rate (retention time in the bowl)

Increased bowl speed increases the centrifugal force acting on the particles and increases their settling velocity. The bowl speed should be maintained at 1600 to 1800 rpm to effectively settle barite particles in the 3-4 micron range. Slower speeds allow more of the small barite particles to escape to the overflow and be discarded. There is a tendency to run the centrifuge at slow speeds in order to increase the life of the bearings. This reduces the efficiency of barite recovery and increases mud costs.

Water is fed into the centrifuge with the mud in order to reduce the mud viscosity and allow increased settling rates. The more dilution water used, the greater will be the reduction in viscosity. However, if too much water is used, the mud feed rate will need to be reduced to keep from overfeeding the centrifuge. In other words, the centrifuge can effectively process only so much mud-water mixture without exceeding its capacity. The water feed rate for good separation efficiency will usually be between 25 and 75 percent of the mud feed

Continued on next page

Centrifuge Continued

rate. High density and high yield point muds will require more dilution than muds of lower density or yield point.

The total feed rate to a centrifuge must be limited. If the rate is too high, the mud will flow to the overflow ports before sufficient time has elapsed to allow all of the barite particles to settle. The maximum feed rate for efficient operation is a function of mud weight. As mud weight is increased, the feed rate should be decreased. Feed rates may range from 20 gal/min at 12 lb./gal to 6 gal/min at 18 lb./gal mud weight. In the final analysis, the feed rate should be decreased if barite recovery is less than desired.

It is a common misconception that the underflow from a centrifuge consists only of barite. The drilled solids are also subjected to the same settling forces. Those approximately 1.5 times larger than the smallest barite particles which settle to underflow will also settle at the same rate. As a consequence, the underflow will contain the coarser drilled solids as well as barite.

In effect, all these particles are settling out of that portion of the mud which becomes the overflow, and they settle into the remainder of the mud. As a result, the underflow will consist of these settled particles surrounded by the diluted mud that was fed to the centrifuge. A portion of everything that was originally in the mud will also be in the underflow.

Continued on next page

Centrifuge

Continued

As the solids concentrate in a settling process, the density difference between a particle and the high-density slurry around it decreases quite rapidly. These factors limit the concentration of solids in the underflow of a centrifuge to approximately 55 percent. The underflow will usually weight from 23 to 23.5 lb./gal, depending on the amount of drilled solids it contains. Consequently, the density of the underflow cannot be used to evaluate the performance of the centrifuge.

The overflow consists of the diluted mud that was fed to the centrifuge, minus those solids which settled out of it. Its density will depend on the amount of solids that did not settle to the underflow. The density will increase as the amount of barite left in the overflow increases.

A good, quick means of checking the performance of a centrifuge is to simply measure the density of the overflow. Generally, a density of 9.3 to 9.5 lb./gal indicates good performance. Higher densities indicate that the cut point is too high and substantial amounts of barite are being discarded. The bowl speed, dilution rate, and mud feed rate should be checked and appropriately changed.

When the centrifuge is operating correctly, the underflow will contain 90-95 percent of the barite in the mud processed. The remainder will be discarded in the overflow. The underflow will also contain about 15-30 percent of the original feed mud. As a result, it will contain a

Continued on next page

Centrifuge Continued

like amount of the bentonite and chemical in the original mud. The remaining 70-85 percent will be discarded with the overflow. The drilled solids in the original mud contained in the underflow plus all of the larger settled particles will remain in the underflow. The exact amount depends on the size distribution in the mud. If all the drilled solids are smaller than the cut point of the centrifuge, a maximum of 70-85 percent will be removed. Generally, about 30-60 percent will be removed.

When the underflow is returned to the active mud system, it must be rebuilt into mud of the proper density containing the desired amounts of bentonite and chemical. This means that additions of water, bentonite, and chemical must be made. Since 70-85 percent of the bentonite and chemical are discarded in the overflow, this amount should be replaced in order to keep from "stripping" the mud. If too much bentonite is added, the flow properties will increase and dilution will be required. Consequently, bentonite additions should be carefully controlled in order to control the flow properties. A procedure for determining the required amounts is given in **Appendix B**.

Some solids are discarded in the overflow. This means that the mud volume reconstructed from the underflow will be less than the volume processed. If the volume of the mud system is maintained constant, a small amount of new mud will need to be built. Normally,

Continued on next page

Centrifuge Continued

this will run 5-15 percent of the volume centrifuged. In other words, if 20 bbl/hr of mud is being centrifuged, from 1 to 3 bbl/hr of new mud should be built. If the barite consumption is greater than the amount required to make this amount of mud, either the centrifuge is discarding an excessive amount of barite or the system is being diluted with new mud volume.

Since the centrifuge processes only a small fraction of the mud returns and removes half or less of the drilled solids in the mud which is processed, it is not capable of reducing the total solids content of a mud while drilling. Consider the case where one-third of the mud system is centrifuged in one day. If the mud contains 6 percent drilled solids and one-half of the drilled solids are removed from one-third of the mud, a one percent reduction in drilled solids would result. However, one percent additional solids could be added to the system in one day of drilling. At the end of one day the mud would still contain 6 percent drilled solids.

This analysis shows that the centrifuge may be capable of keeping the drilled solids content from increasing, but will not effectively reduce the concentration. The drilled solids content of a weighted mud must start at a low level if it is to be maintained at a low level. Since the centrifuge selectively removes the smallest particles, it is quite effective in controlling the flow properties. Small hydrated clay

Continued on next page

Centrifuge Continued

particles are almost totally responsible for excessively high plastic viscosities, yield points, and gel strengths. By removing these small particles and adding an adequate amount of bentonite, the filter cake properties are also improved. These are the primary reasons for centrifuging a mud.

Arrangement of Solids Control Equipment

Figure 8 shows the recommended arrangements of the solids control equipment for unweighted and weighted mud systems. In general, the various pieces of equipment are arranged in decreasing order of their cut points as the mud proceeds downstream from the flowline.

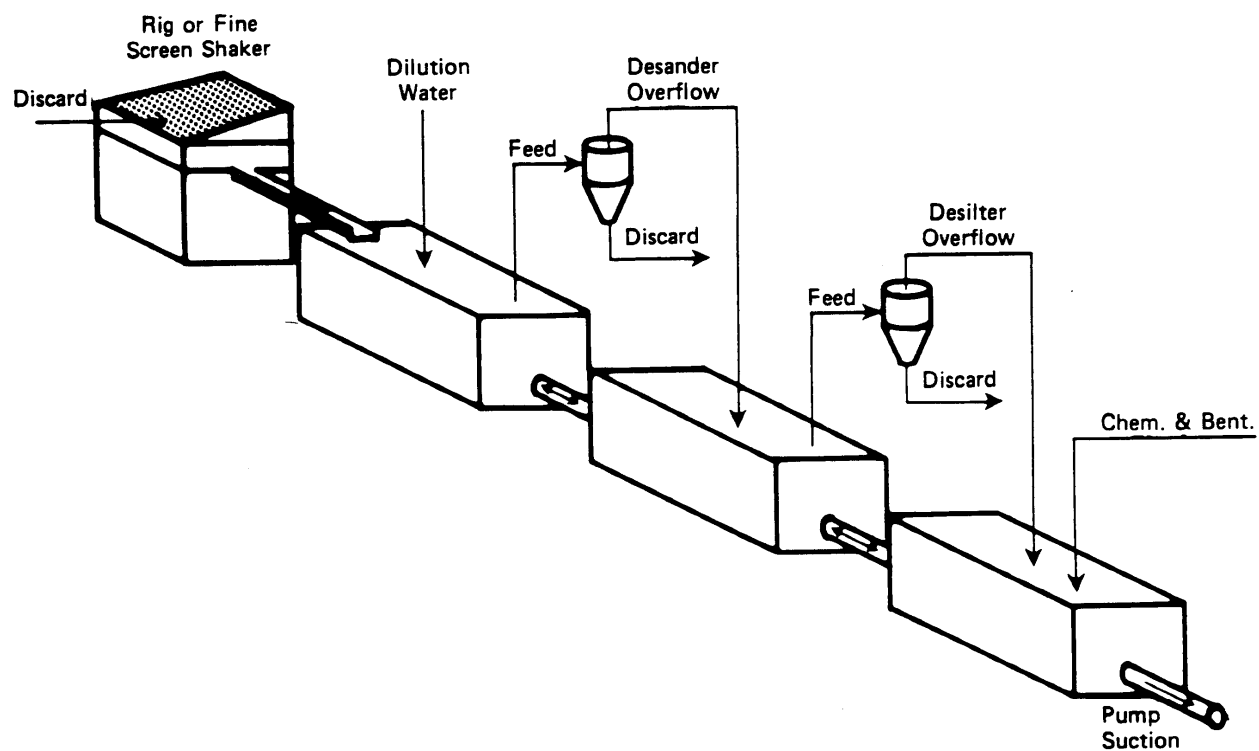
Any dilution water used should be introduced ahead of the solids-removal devices in order to improve their separation efficiency. Additions of all other mud materials should be made downstream from the last solids-removal device.

The feed and discharge of each device should be separated so that newly processed mud is not fed back to the device. Preferably, the feed and discharge should be in alternate pits. The discharge end of the overflow pipe from a desilter or desander should be above the mud level. If it is not, the separation efficiency will be reduced and mud can siphon back through the cones and out the underflow when the pump is shut down.

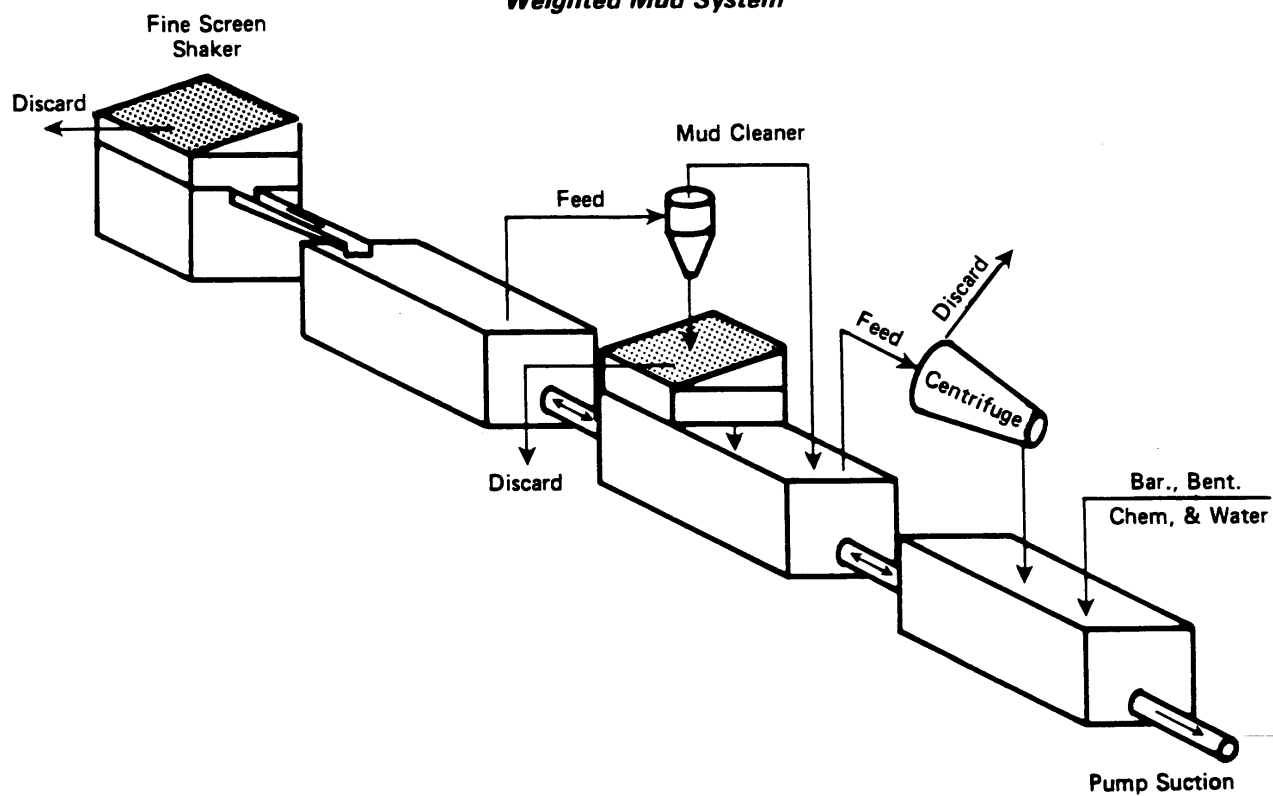
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Figure 8

Unweighted Mud System



Weighted Mud System



Section VII

PRODUCTION DESCRIPTION

Weighting Agents- Barite

Barite is a naturally occurring mineral which is mined and ground to API specifications. It is predominately barium sulfate, but contains some impurities. The minimum specific gravity allowed by API is 4.2 compared to a 4.5 specific gravity for pure barium sulfate. The impurities vary depending upon the source of the ore but are predominantly inert materials such as quartz. Pure barium sulfate is white, but impurities often cause barite to be gray or pink. However, the color is not indicative of the purity or quality of the barite.

The only impurity that is specifically limited by API specification is the soluble alkaline earth metals, limited to 250 mg/l expressed as calcium. Cement is a detrimental contaminant that may get into barite when it is transported. Other detrimental contaminants are the caustic extractable heavy metal carbonates and sulfides. Exxon usually limits caustic extractable carbonates to 3000 mg/l and sulfides to 50 mg/l.

The API specifications for barite are found in API Spec 13 A, "Oil-Well Drilling-Fluid Materials."

Hematite

Hematite is a naturally occurring iron oxide mineral. The product used as a weighting agent in mud is a micaceous hematite mined in Brazil. It is a very pure material having a specific gravity of approximately 5.1. It is harder than barite and as a result, can be more abrasive under some conditions. To minimize the abrasive potential, it should be ground so that no more than 0.5% will be retained on a 200 mesh screen. API specifications for this product are under study.

Clays - Wyoming Bentonite

Wyoming bentonite is a naturally occurring bentonite which is mined in Wyoming. There are no other commercial sources of this mineral of comparable quality. It is predominately sodium montmorillinite, but contains some calcium bentonite and sand or silt. As a result, it is somewhat variable in performance.

When the product fails to meet the API specs for viscosity yield, it is often treated with a polymer to increase the viscosity. The polymer causes a form of flocculation that increases the YP of the suspension at API test conditions. This may allow the product to pass the test but does not improve its performance at high temperatures or in a treated mud. Its performance under most conditions is a function of the original quality of the clay. Filtration

Continued on next page

Wyoming Bentonite

Continued

tests are probably the best way to evaluate the quality of the product.

API specifications for bentonite may be found in API Spec 13A. In addition to the old original spec that allows polymer treatment of the product, there is a new spec (1987) for non-treated bentonite. This new spec should be used in high weight muds and when fluid loss is of primary importance.

Sub Bentonite

The sub bentonites are primarily calcium bentonites of poor quality. It was once popular to add these clays to muds in order to get a particle size mix. This is completely unnecessary and simply adds to the solids concentration of a mud. The reduction in fluid loss which was claimed for these products was a result of thicker filter cakes. These clays are very similar to the clays contained in bentonitic shales and should not be used.

Beneficiated Bentonite

These products are Wyoming bentonite treated with a polymer, usually a polyacrylate, to cause flocculation. The result is a product which produces suspensions of about twice the viscosity of ordinary Wyoming bentonite. The same performance can be achieved at less cost by treating a bentonite suspension with a flocculating polymer,

Continued on next page

**Beneficiated
Bentonite**
Continued

lime, or soda ash. The only advantage of this product is that it comes in one sack.

It is ineffective in any environment where the polymer is ineffective such as salt water, calcium contamination, and high temperature.

Attapulgate

Attapulgate is a naturally occurring clay mineral which is mined in Georgia. Unlike other types of clays, it is a needle shaped non-swelling particle. It derives its viscosity building from its shape and surface charge. For this reason, it is unaffected by water salinity. It will produce as much viscosity in saturated salt water as it will in fresh water. Since it depends to a large degree on natural occurring flocculation to produce high yield points and gel strengths, a small amount of thinner will completely destroy the viscosity of an attapulgate suspension.

An attapulgate particle is actually a bundle of these fine individual needles. High shear is required to break up these bundles and disperse the needles. As a result, the viscosity of an attapulgate suspension is dependent on achieving a high degree of shear.

Since the particles are needle shaped and non-swelling, attapulgate offers no fluid loss control. Its primary use is to build yield point and gel strength in a saltwater mud.

Thinners - Lignosulfonate

The lignosulfonates used to treat drilling fluids are basically sulfonated lignins complexed with chrome or iron and chrome. The starting raw material is spent sulfite liquor which is a waste product from the paper industry. Since the basic raw material is a waste product, the finished product is cheap compared to the cost of a product tailor-made from pure raw materials. For this reason, it will be difficult to ever replace this product with anything comparable or better at the same price.

Lignosulfonate is essentially 100 percent soluble in water. It forms an acid solution with a pH of about 4.0. The lignosulfonate molecule is quite complex. It is a large anionic molecule which adsorbs at the positive charge sites on clay platelets. By neutralizing the positive charges, it keeps clay particles from linking together in a state of flocculation. This causes a reduction in yield point and gel strength of a mud.

Lignosulfonate degrades at high temperatures. As it degrades, small amounts of carbon dioxide are liberated. Over a period of time, this can lead to a carbonate or bicarbonate problem. At low pH, degradation may occur at temperatures as low as 250°F. At a pH of 10 or higher, degradation is retarded. The active lignosulfonate content of a mud is reduced about 2 lb./bbl in 16 hours at 300°F. Very rapid degradation occurs at temperatures above 350°F. At this temperature, hydrogen sulfide is liberated in small quantities.

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Lignosulfonate

Continued

Lignosulfonate works best at a pH of 9.5 to 11.5. At this level, the degradation is slowed and its ability to deflocculate is enhanced. About 2-4 lb./bbl active content is required in freshwater muds to achieve maximum deflocculation. Approximately twice this amount is required in saltwater muds.

Common Lignite

A lignite mineral known as Leonardite is mined in North Dakota. This mineral is ground and sold as lignite to be used in treating muds. It is the humic acid content of this material that functions as a thinner.

It has a very low solubility when added to water, but increases in solubility as pH is increased. It is about 75 percent soluble as a maximum. It is an acid material and forms solutions with a pH of about 4.5. When reacted with calcium, it forms an insoluble precipitate.

The fact that it is an acid and precipitates calcium makes it a very good material to treat cement contamination. Concentrations above 10 lb./bbl should be avoided. Calcium added to such a solution will form a rigid gel.

Lignite is an adequate thinner at low temperatures, but at temperatures above 250°F it does not deflocculate sufficiently well. It has been mistakenly considered a high temperature thinner simply because it has a thermal stability above 400°F.

Continued on next page

Common Lignite

Continued

The primary function of lignite is as a fluid loss-control additive. Lignite, lignosulfonate, and bentonite at equal concentrations will each reduce the fluid loss of a mud an equivalent amount.

Causticized Lignite

Causticized lignite is a blend of 1 part caustic to 6 parts lignite. In solution it has a pH of about 9.5. Its cost is approximately 40 percent higher than the combined costs of the lignite and caustic that it contains.

The performance of this product is no different from that of lignite and caustic added separately. Its only advantage comes from the fact that it contains enough caustic to solubilize when added to water. This is a disadvantage when treating cement contamination, since the acid behavior of common lignite helps to neutralize the hydroxyl effect.

Modified Lignite

There are a number of ways that lignite can be modified. First, it can be neutralized by the addition of a base. Some products have been neutralized by addition of potassium hydroxide. The potassium ion is supposed to aid in shale stabilization.

Continued on next page

Modified Lignite

Continued

Lignite can also be modified by complexing with a heavy metal. The heavy metals supposedly add temperature stability to lignosulfonate treated muds. The addition of both potassium and the heavy metal is detrimental to fluid loss control. These products are expensive and unwarranted for most applications.

Querbracho

Quebracho is a tannin extract from the quebracho tree. It is a quite effective thinner requiring only 1 to 2 lb./bbl to deflocculate a mud. For best results, it should be used at a pH above 11. It is not effective in calcium or salt muds or at temperatures above 225°F.

It is often blended with lignite to improve its fluid loss control characteristics and extend its temperature limitation.

Closely related to quebracho are some products which are hemlock tannin extracts. These products will perform slightly higher salinities (up to about 20,000 mg/l chloride).

Phosphate

Polyphosphates are good deflocculating agents in freshwater muds at low temperatures. Approximately 0.1 to 0.2 lb./bbl will completely deflocculate a mud. There are several polyphosphates which are used in mud treating.

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Phosphate

Continued

Sodium tetrphosphate is the most common form used as a mud thinner. A one percent solution has a pH of about 8.5. Phosphate treated muds are normally run at a pH of about 9. It will not function as a thinner in the presence of calcium or high salt concentrations. It is a sequestering agent for calcium and is often used for the purpose. However, it should not be used to treat for cement contamination since it is an alkaline material. An acid form of phosphate, SAPP (sodium acid pyrophosphate) is a preferred treating agent for cement contamination. It has a pH of about 4.0.

At temperatures above 180°F, the polyphosphates are converted to orthophosphate which is a flocculating agent. This establishes the upper temperature limit for use of phosphates as thinners.

Another polyphosphate which is used as a thinner is tetra sodium pyrophosphate. It is more alkaline than sodium tetrphosphate, but otherwise functions in much the same manner. A one percent solution has a pH of about 10.1.

Polymers

There are basically two types of water soluble polymers used in muds. They are the natural polymers, polysaccharides, and the synthetic, vinyl polymers.

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Polymers

Continued

The natural polymers consist of starch, modified cellulose (CMC and HEC), gums, and Xanthan polymer. These materials increase the viscosity of water due to their molecular size, shape, and ability to absorb water.

The vinyl polymers consist of partially hydrolyzed polyacrylate and vinylacetatemaleic anhydride co-polymers. The performance of these polymers varies considerably due to difference in molecular weight and degree of hydrolysis. However, they have a number of points of similarity. They increase the yield point of clay suspensions by adsorbing on the clay particles and linking them together.

The synthetic polymers, which depend on adsorption, are inherently sensitive to their environment. Calcium is especially detrimental. They react with calcium and become insoluble, causing high viscosities and gelation of the mud.

The natural polymers, which perform by thickening water, are essentially non-charged and are less sensitive to their environment. Starch and HEC will perform in almost any kind of brine, and Xanthan polymer will perform in salt water. CMC loses its effectiveness in salt water, above 50,000 mg/l chloride. Gums such as guar gum are sensitive to calcium and pH, and should not be used in calcium concentrations above 250 mg/l and pH above 9.5.

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Polymers

Continued

Starch, CMC, and HEC are primarily fluid loss control agents but also may be used as viscosifiers. Guar gum is primarily used to viscosity brine workover fluids. It imparts some fluid loss control. Xanthan polymer is a viscosifier and affords very little fluid loss control.

More information on the use of polymers is given in Section 4 under Treating Agents.

Oil Muds

An oil mud is basically oil (usually diesel oil) with water emulsified into it and supplemental materials added to impart viscosity, fluid loss control and oil wetting of the solids.

A primary emulsifier is used to stabilize the emulsions and supply some viscosity and fluid loss control. If the mud is to be used at temperatures above 275-300°F or if calcium chloride water is to be emulsified, a supplemental emulsifier is normally added.

All of the solids in an oil mud must be wet with oil to prevent aggregation of the solids and weakening of the emulsion. An oil-wetting agent is used for this purpose.

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Oil Muds

Continued

To prevent settling of barite and supply hole cleaning capability, supplemental viscosifying agents are sometimes needed. Supplemental fluid loss control agents are also used in some cases, especially at very high temperatures.

All of the oil mud product lines contain these basic materials. Individual products are often blends of more than one of these materials. The types of chemicals used to perform these various functions are often different in the various oil muds, leading to finished muds of different characteristics.

Section IX

IDENTIFICATION AND TREATMENT OF CONTAMINANTS

Identification and Treatment of Contaminants

The most common chemical contaminants of water-base muds are:

1. Cement
2. Calcium or Magnesium
3. Salt
4. Carbonates and Bicarbonates

All of these contaminants cause the mud to flocculate, resulting in increased yield point, gel strength, and fluid loss. Since the physical effects on the mud are much the same, chemical analysis of the mud and filtrate is necessary to identify which contaminant is present.

Cement

The active part of cement that causes mud problems is lime, Ca(OH)_2 . As cement sets, the amount of active lime in the cement decreases. In green or unset cement, the active lime content is quite high while fully cured cement has very little active lime. This makes

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Cement Continued

it impossible to predict the extent of contamination that will occur, even when the amount of cement to be drilled is known.

Lime has a relatively low solubility so that only a fraction of a pound per barrel will go into solution depending on the conditions of temperature, pH, and salinity. Both increased temperature and pH decrease the solubility of lime while increased salinity increases its solubility. Normally, only 0.25 to 0.5 lb./bbl of lime will go into solution in a mud. The remainder of the lime will remain in the mud as undissolved particles.

When enough lime or cement has been added to a mud to reach the limit of solubility, the pH will normally be in the range of 12.0 to 12.6 and the calcium concentration will be approximately 100 to 600 mall. If the mud has a high pH originally, the resulting pH after addition of lime or cement will be in the high part of this range and the calcium content in the low part of the range. Conversely, if the pH is initially low, addition of lime or cement will result in a pH near 12.0 and a higher calcium content. When cement is drilled and these conditions are not met, it means that less lime went in solution than is required for saturation. Consequently, very little if any treatment to chemically remove the lime will be necessary.

Diagnosis

As lime is added to a mud, the pH, Pf, and Pm will increase until the limit of lime solubility is reached. At this point, the pH and Pf will stop increasing since they are measuring only the alkaline material in solution. However, Pm will continue to increase as lime is added, because it is measuring the total alkaline material in the mud, both dissolved and undissolved. When the pH is high (approximately 12 or higher) and $Pm > 3Pf$, an excess of cement or lime is indicated. The amount of undissolved lime in a mud can be estimated from the following equation:

$$\text{Undissolved lime, lb./bb} = 0.26 \left[Pm - \frac{\% \text{water}}{100} (Pf) \right]$$

When the cement is green, it will disperse in the mud into fine particles. The greater surface area will allow more reaction with the mud and more severe flocculation problem. It is better to dump the most severely contaminated mud rather than try to restore it with chemical treatment. The mud cleaner and centrifuge should be used on a weighted mud to remove the fine particles and the desander and desilter should be used on an unweighted mud.

After all of the cement has been removed that can be removed by the solids control equipment, chemical treatment can be used to restore the mud to its desired properties. A choice must be made whether to convert the mud to a lime mud or to precipitate the lime.

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Diagnosis

Continued

If the choice is to convert to a lime mud, lignosulfonate is added to deflocculate the mud and perhaps more lime added to break over the mud. It should be remembered that this mud will be less temperature stable and have a higher fluid loss than the original mud before contamination. Some dilution may be required in the break over, thus requiring prehydrated bentonite additions after break over.

Precipitation of lime requires the use of a material that will neutralize the hydroxyl ion as well as precipitate the calcium. Sodium bicarbonate and sodium acid pyrophosphate (SAPP) are the two most commonly used treating agents. To react with one pound of lime requires 1.135 pounds of sodium bicarbonate or 1.498 pounds of SAPP. Both of these materials will precipitate all of the calcium and neutralize half of the hydroxyl ions in the lime. The remainder of the OH ions are converted to caustic (NaOH). For every pound of lime that is treated out, 0.54 pound of caustic will be formed. This means that the pH of the mud will increase when the undissolved lime is reacted with sodium bicarbonate or SAPP. This makes it very difficult to treat out large amounts of lime or cement without causing a caustic reaction which will flocculate the mud. Lignite and lignosulfonate are acid materials which can be used to neutralize the caustic which is formed and also deflocculate the mud. About 3 lb./bbl will neutralize the caustic formed from 1 lb./bbl of lime.

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Diagnosis

Continued

Neither soda ash nor one of the alkaline forms of phosphate should be used to treat cement. These materials precipitate calcium but do not neutralize any hydroxyl ions, thus causing the pH to increase more rapidly. Causticised lignite should not be used for the same reason.

Precipitation reactions occur in the water phase. As the lime in solution reacts with the sodium bicarbonate or SAPP, some of the undissolved lime goes into solution to replace it. The reaction will continue until all of the treating agent has been used up or until all of the lime has been dissolved and reacted with the treating agents. Since the lime must first be dissolved before it reacts with the treating agent, the reaction goes slowly. It is best to treat out the lime in steps rather than attempting to treat it all in one step. This avoids the problem of having a high concentration of treating agent in the mud waiting to react with the lime and being available to react with the clay solids.

Even before lime is added to a mud, the P_m will usually be greater than the P_f . This is due to other forms of undissolved alkaline material in the mud such as hydroxyl ions absorbed on clay particles. If the undissolved lime content is calculated from the equation above both before and after cement contamination, the

Continued on next page

Diagnosis Continued

difference between these two values should more accurately indicate the true amount of undissolved lime.

The total amount of lime, both dissolved and undissolved, can be estimated by multiplying the increase in P_m due to cement contamination by 0.26

$$\Delta P_m \times 0.26 = \text{Total lime. ;b/bbl of mud}$$

Effects on Mud Properties

Addition of cement or lime to a mud will cause the mud to flocculate, resulting in increased YP, gel strength, and fluid loss. The degree of flocculation will depend on the solids content of the mud and the presence of enough thinner to offset the flocculating tendency of the lime. Since it is the flocculation of solids that causes the detrimental effects on mud properties, a high concentration of active solids will result in a more pronounced effect on the mud properties. The more dispersed clay solids that a mud contains, the more difficult it is for the lignosulfonate to keep these solids from flocculating when exposed to cement or lime. If the mud contains no deflocculant, then it will flocculate even with a relatively low solids content. Thus, the effect of cement contamination will vary from mud to mud. In general, an untreated or lightly treated mud or one with a high active solids content will react more violently than a highly treated, low solids mud.

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Effects on Mud Properties

Continued

The cause of flocculation in a cement or lime contaminated mud is probably due to the high pH which is generated rather than the relatively small amount of calcium that goes into solution. Even a rapid increase in pH from caustic addition will cause a mud to temporarily flocculate. Perhaps an even more important effect is due to the surface reaction between fine particles of lime and the clay particles which come in contact with them. The result is severely flocculated mud surrounding each lime particle. With enough lime particles, the entire mud volume becomes flocculated.

The addition of a very small amount of lime will temporarily flocculate a mud due to the surface reaction of the particles with the clay particles. In time, after all of the lime has gone into solution, the mud will become thin again. In fact, it may become less viscous than it was originally due to dehydration of the clay platelets by the lime. It is this effect of inhibiting hydration and dispersion that causes the fluid loss of a mud to remain high even after the mud has been thinned by addition of a deflocculant.

Treatment

Since the particles of cement or lime in a mud are a large part of the problem, the first step in treatment is to remove as many of these particles as possible. When the cement is cured, the drill cuttings will normally be large enough that they can be screened from the

Continued on next page

Treatment

Continued

Overtreatment with sodium bicarbonate and SAPP should be avoided since both will cause the mud to flocculate. When SAPP is heated to 180°F, it converts to orthophosphate which is a flocculant and the bicarbonate ion is also a flocculant. A complete mud check should be made after each treatment to avoid overtreatment. When the Pm has been reduced to three times the Pf, treatment should be stopped.

The decision of whether to use sodium bicarbonate or SAPP will normally be made based on cost and availability. The only difference in performance is that a slight overtreatment with SAPP will thin the mud since it is a deflocculant. However this would only occur at temperature less than 180°F.

Pretreatment

The question often arises as to whether a mud should be pretreated before drilling cement. If the pretreatment has the potential of damaging the mud properties. Then it should not be used. Since the amount of active lime which will get into the mud is never known. It is impossible to prescribe the correct amount of treating agent beforehand. An over treatment with either sodium bicarbonate or SAPP is potentially as harmful to the mud as is the cement.

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Pretreatment
Continued

The best pretreatment is elimination of unnecessary solids from the mud and treatment with lignosulfonate and lignite. These additives will combat the tendency of the mud to flocculate and prevent the most severe reactions of cement on the mud.

**Calcium and
Magnesium**

Calcium and magnesium are closely related ions and have similar effects on mud properties. They replace sodium ions on bentonite, thereby reducing the degree of hydration, and promoting flocculation and aggregation of the bentonite platelets. This leads to increases in yield point, gel strength, and fluid loss of the mud.

Calcium and magnesium may enter the mud system from several different sources such as make-up water, saltwater flows, contaminated mud products, and drilling of gypsum or carnallite. Seawater, for instance, contains about 1250 mg/l of magnesium and 425 mg/l calcium. If well water is used for make-up water, it may contain these ions and should be checked periodically. Formation saltwater may also contain various amounts of calcium and magnesium. Some of the mud products such as barite may contain calcium. The API specifications for barite allow up to 250 mg/l calcium in the barite. This is equivalent to approximately 0.11 pound of gypsum per sack of barite. Gypsum or anhydrite beds are also a common source of calcium.

Diagnosis

The combined calcium and magnesium concentration (total hardness) in a mud filtrate is normally measured in a mud check and reported as calcium in mg/l. If the actual calcium and magnesium concentrations are desired, it is necessary to run a second titration using another indicator specific to calcium. This test gives the calcium concentration and the magnesium concentration can then be calculated by the difference between the two titrations.

Magnesium, mg/l = $0.606 (\text{Total Hardness, mg/l} - \text{Calcium, mg/l})$

When the pH of the mud is above 10.5, essentially all of the magnesium has been precipitated as magnesium hydroxide and the total hardness test will indicate the true calcium content of the filtrate. If the mud pH is below 10.5, both calcium and magnesium can exist in the filtrate. In this case, both titrations must be run to determine their concentrations.

Mud filtrates often contain organic treating agents such as lignite and lignosulfonate that interfere with the calcium and magnesium determination. These materials complex some of the calcium and magnesium ions, thus making them unavailable for reaction.

However, these complexed ions are measured in the titration as if they were free ions in solution. In other words, a filtrate that has no free calcium ions in solution may indicate as much as 100 to 200 mg/l. If the mud is well treated, this amount of calcium will probably not cause problems in any case.

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Diagnosis

Continued

Addition of calcium or magnesium will cause several changes in the mud system in addition to an increase in the total hardness. A reduction in pH will normally occur. This is much more pronounced from magnesium additions than from calcium due to the reaction of magnesium with hydroxyl ions to form insoluble magnesium hydroxide, $\text{Mg}(\text{OH})_2$. Lime is much more soluble than magnesium hydroxide so that the resulting decrease in pH will be less.

Calcium and magnesium will also cause an increase in fluid loss due to the strong dehydrating and flocculating effects of these ions on bentonite. Even in cases where the effect of flocculation is counteracted by lignosulfonate, the fluid loss will be increased due to dehydration of the bentonite.

Flocculation of the mud is the most serious effect of calcium or magnesium. This causes an increase in yield point and gel strength of the mud. The severity of the problem is a function of the concentration of the active clay solids, the amount of calcium or magnesium introduced into the mud, and ability of the thinner to counteract flocculation. Flocculation from any cause is always aggravated by a high solids content. If the concentration of calcium or magnesium in a mud gets high enough, it will overwhelm any thinner and cause flocculation. Temperature is also important because increased temperature also promotes flocculation and will increase the severity of a contamination induced problem.

Continued on next page

Diagnosis

Continued

In summary, an increasing trend of total hardness or a sudden increase to values above 200 mg/l signals the presence of calcium or magnesium in the filtrate. The harmful effects on mud properties will be increased fluid loss, yield point, and gel strength. The pH will decrease, especially from addition of magnesium, and the plastic viscosity will tend to decrease as the hardness ions reduce the hydration of the bentonite platelets.

Effects on Mud Properties

In addition to the effects of dehydration and flocculation of bentonite that have already been discussed, calcium and magnesium also affect other mud additives. Many of the polymers and lubricants are sensitive to water hardness.

The synthetic vinyl polymers (polyacrylates, etc.) react with calcium and become insoluble. Gelation of the mud and high viscosities that cannot be controlled will develop at calcium concentrations above 200 mg/l.

Many of the natural polymers are also sensitive to calcium. CMC loses its ability to hydrate as calcium concentration is increased. At concentrations above 1000 mg/l, it becomes ineffective. Gums such as guar gum are sensitive to calcium and should not be used where

Continued on next page

Effects on Mud Properties

Continued

calcium concentrations are above 250 mg/l. Of the commonly used polymers, only starch and HEC perform well at high calcium concentrations.

Many of the lubricants that contain fatty acids or vegetable oils form calcium soaps and "grease-out" in the presence of calcium. This can cause the barite and mud solids to become oil-wet and agglomerate, leading to serious settling and high viscosity problems.

Many other mud additives "salt-out" or become ineffective in the presence of high calcium or magnesium concentrations. Lignite is precipitated by hardness ions. The precipitant appears to be hydrated, thus building viscosity. High viscosities may develop if more than 6 to 10 lb./bbl of lignite is precipitated in the mud. Lignosulfonate also becomes ineffective at high hardness concentrations.

Treatment

The treatments for calcium and magnesium are different and must be considered separately. However, the first line of defense against any type of contaminant is to maintain a mud with a minimum clay solids content. This is true because the effect of the contaminant on the clay solids is responsible for the changes in mud properties that occur. The source of the contaminant is also important in selecting

Continued on next page

Treatment Continued

the type of treatment to use. If the amount of contaminant is small or non-recurring, the decision will normally be to precipitate it from solution. However, if the amount of contaminant is quite large or a continuing feed-in, the decision may be to treat or convert the mud to a type that will tolerate the contaminant. For instance, if a long interval of gypsum is to be drilled, the mud may be converted to a gyp mud rather than continually treating the mud to precipitate the calcium that goes into solution.

To convert to gyp mud, some dilution may be necessary if the active solids content is too high. Approximately 2 to 4 lb./bbl of lignosulfonate should be added to deflocculate the mud and caustic added to increase the pH to at least 10. The calcium content in the filtrate will range from 300 to 1200 mg/l depending on the pH of the mud. A high pH decreases the solubility of calcium and limits the calcium content in the filtrate. After the mud is deflocculated, the clay platelets will tend to aggregate face-to-face, causing the mud to become even less viscous and the fluid loss to increase.

Prehydrated bentonite may be required to support the barite and reduce the fluid loss. At temperatures below 250°, fluid loss control polymers such as starch or CMC may also be used.

Caustic should be added to a mud to precipitate magnesium. Precipitation will begin when the pH reaches 10 and will go to

Continued on next page

Treatment

Continued

completion at a pH of 10.5. One lb./bbl of caustic will precipitate 864 mg/l of magnesium. Magnesium precipitates as a very fine particle, and at high concentrations will gel water. Consequently, no more than a few thousand mg/l can be precipitated without causing severe increases in the mud viscosity.

Soda ash is normally used to precipitate calcium. One lb./bbl of soda ash will precipitate 1078 mg/l of calcium. Care should be taken not to over treat with soda ash. This could result in development of a carbonate problem. Treatment with soda ash should be calculated to leave approximately 100 mg/l of calcium in solution.

Since gypsum has a limited solubility, the filtrate analysis for calcium may not indicate the total amount of calcium in the mud. As calcium is precipitated from the water, additional gypsum will go into solution. Repeated treatments with soda ash will be required until the filtrate calcium has been reduced to the desired level.

After precipitation of either calcium or magnesium, fresh lignosulfonate should be added to replace the lignosulfonate that has been lost due to physical extraction by the precipitation process. Caustic additions will also be required to adjust the pH to the desired level.

Salt

The salinity of water affects the hydration, dispersion, and flocculation behavior of clay particles. As salinity is increased, the degree of hydration is decreased and the tendency to flocculate is increased. This has pronounced effects on both the filtration and flow properties of a mud.

The common sources of salt are make-up water, saltwater flow, and drilling of salt beds. It is important to determine the source of a salinity increase so that proper remedial action can be taken. The salinity of the make-up water should be frequently checked in order to determine if a change in mud salinity is due to the make-up water or from a downhole source.

Diagnosis

Detection of salt or saltwater in a mud is relatively easy. It is measured by titrating the filtrate for chloride ion concentration and is reported as mg/l of chloride ion in solution. The sodium chloride concentration is 1.65 times the chloride concentration.

It is normal for the chloride concentration to slowly increase in the mud while drilling a well due to grinding up rock that contains saltwater and due to evaporation of water from the mud causing the salt to be concentrated. This is offset to a degree by additions of freshwater to the mud. This will cause minor fluctuations in salinity.

Continued on next page

Diagnosis

Continued

However, any sudden increase in chloride concentration of more than a few hundred mg/l indicates that salt or saltwater from some source is entering the mud system.

A significant increase in salinity will cause the mud to flocculate. The yield point, gel strength, and fluid loss will all tend to increase. The amount of increase will depend on the amount of active solids in the mud, the amount of lignosulfonate, and the amount of increase in salinity. The pH of the mud will also be decreased and a slight increase in total hardness may occur. The increase in sodium ions from the salt may exchange some of the calcium from the clay solids and cause the total hardness of the filtrate to increase by 100 to 200 mg/l.

In order to differentiate between a saltwater flow and drilled salt, it may be necessary to estimate the volume of formation water influx that would be required to cause the observed increase in salinity. If an increase in much volume of this amount cannot be accounted for, the increase in salinity must have been caused by drilled salt. The volume of formation water necessary to cause the increase in mud salinity can be calculated as follows:

$$V_w = \frac{V_m(C_2 - C_1)}{C_w - C_2}$$

Continued on next page

Diagnosis

Continued

Where:

V_w = Volume of formation water

V_m = Volume of mud in which salinity change has taken place

C_1 = Original salinity of the mud

C_2 = Final salinity of the mud

C_w = Salinity of formation water

Formation waters may contain significant amounts of calcium and magnesium chloride as well as sodium chloride. In these cases, large increases in total hardness will occur. For pure calcium chloride water, a calcium to chloride ratio of 40 to 71 will exist. If the formation water contains magnesium, the pH of the mud will rapidly decrease to 9.5 or slightly below due to precipitation of magnesium hydroxide.

Effects on Mud Properties

A chloride increase of a few thousand mg/l will normally cause a mud to flocculate, resulting in increased YP, gel strength, and fluid loss. The degree of flocculation will depend on the active solids content of the mud and whether enough thinner is present to minimize the tendency to flocculate. The salt will also cause

Continued on next page

Effects on Mud Properties

Continued

dehydration of the clay particles. Dehydration is slower than flocculation and may take a day or more before the clay particles completely shrink to a new equilibrium degree of hydration. The result of dehydration is a reduction in plastic viscosity and an increase in fluid loss. If a mud has been treated with lignosulfonate before addition of the salt, the clay platelets are protected from the dehydrating effects of the salt and very little increase in fluid loss will occur.

In summary, the effects of increased salinity on mud properties are largely due to flocculation and dehydration of the active clay solids. These effects are decreased by increased concentration of lignosulfonate in the mud. They are also decreased by decreased active clay solids content. A mud containing a minimum amount of clay solids and 4 to 8 lb./bbl of lignosulfonate will tolerate an increase in chlorides of several thousand mall with minimal effects on the mud properties.

Treatment

Unlike the other contaminants, salt cannot be chemically precipitated. The only way the salinity can be reduced is by dilution with freshwater. This means that the mud treatment must be designed to treat the effects rather than eliminate the presence of the salt.

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Treatment

Continued

Addition of lignosulfonate will deflocculate the mud and thereby reduce the yield point and gel strength. It will also prevent further dehydration of the bentonite and the continued increase in the fluid loss that would normally occur as the bentonite particles continue to dehydrate with time. This makes it important to treat the mud as quickly as possible in order to preserve as much of the original hydration as possible.

If a large amount of salt is to be drilled, the mud will continue to increase in salinity and keep the mud properties in a state of continual change. To avoid this, the mud should be converted to a salt mud. Dilution will often be needed to reduce the active clay solids content. Then the mud should be treated with 4 to 8 lb./bbl of lignosulfonate and salt added until the mud is nearly saturated with salt (chlorides 150,000 to 180,000 mg/l). Prehydrated bentonite can be added as needed to increase the yield point and decrease the fluid loss. If the bottom hole temperature is less than 250°, starch may be added for supplemental fluid loss control.

In a saturated salt mud, maintaining stable mud properties may become difficult at temperatures above 300°F. This is due to precipitation of the lignosulfonate by the salt. Even small amounts of calcium will compound the problem. In case calcium is present in the mud, it should be removed and fresh lignosulfonate added. Extra effort should be made to maintain a low solids mud.

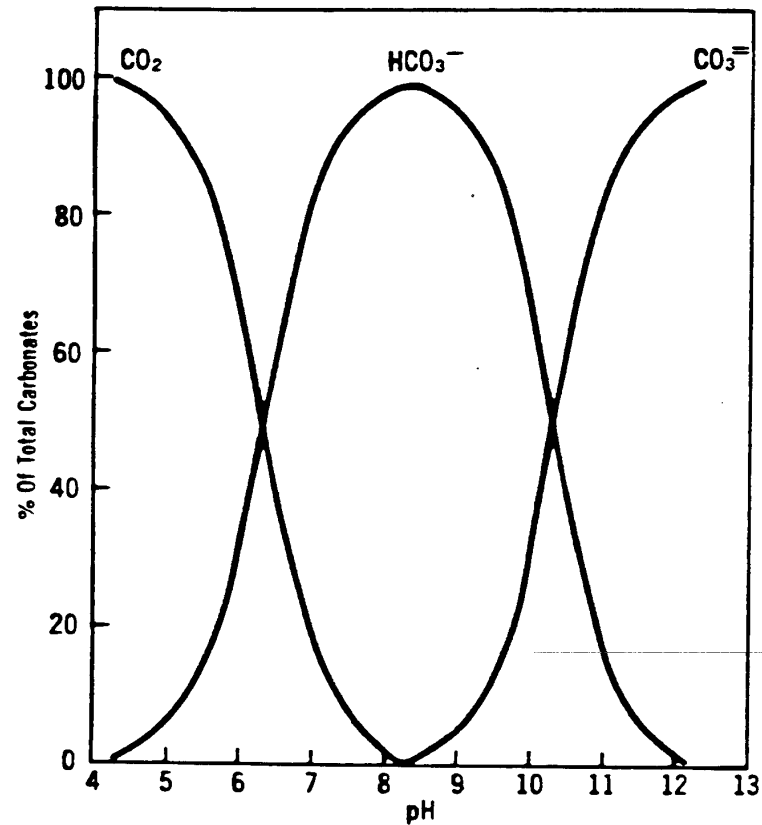
Carbonates

The carbonate family consists of carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3). An equilibrium exists in solution among these three components depending on the pH of the solution. This is illustrated in this figure.

If any one of these three components is added to a water solution, it will be partially or completely converted into the other two components, depending on the final pH of the solution. For example, as CO_2 is dissolved in water, it begins to convert into the HCO_3^- . If the pH of the water is increased to 8.3 by addition of hydroxyl ions (OH^-), the CO_2 will be completely converted to HCO_3^- . Further addition of OH^- , increasing the pH, will begin to convert HCO_3^- to CO_3 . At a pH of 10.3, there will be approximately equal concentrations of HCO_3^- and CO_3 and at pH 11.3, there will be about a 10/90 ratio of HCO_3^- to CO_3 . In this manner, the concentrations of HCO_3^- and CO_3 can be increased as more CO_2 is dissolved in the water. Carbon dioxide can enter the mud from the atmosphere (aeration), from the formation, or from thermal degradation of organic mud additives such as lignosulfonate or lignite. Carbonates can also enter the mud as a result of direct additions of soda ash (sodium carbonate) or sodium bicarbonate or by caustic extraction of some carbonate minerals that are present in some barites.

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Carbonate Equilibria



Carbonates Continued

Regardless of how these ions enter a mud, they can accumulate to a concentration that will cause the mud to flocculate. The reaction with clay solids that causes them to flocculate is not known. However, the HCO_3^- seems to be the primary cause of the flocculation. The

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Carbonates

Continued

concentration that will cause flocculation is dependent on the amount of active solids in the mud and the temperature. A high active solids content and high temperature both promote flocculation and will increase the degree of flocculation induced by any contaminant. In some situations, the first signs of flocculation may occur at HCO_3^- concentrations as low as ten millimoles per liter (610 mg/l).

Unlike others chemical contaminants, the flocculation caused by carbonates cannot be reversed by treatment with lignosulfonate. In fact, if caustic is not added with the lignosulfonate, a reduction in pH will occur, causing more HCO_3^- to convert from CO_3^{2-} and more severe flocculation may occur.

Diagnosis

The diagnosis of a soluble carbonate problem involves either evaluation of alkalinity test results or a direct measurement of carbonates using the Garrett Gas Train (GGT). Often the GGT measurement is not available and an evaluation of alkalinity data must be used to identify the carbonate problem.

The Pf alkalinity is the cc's of 0.02 normal sulfuric acid required to reduce the pH of 1 cc of filtrate to 8.3. In the titration, the acid is consumed in neutralizing the hydroxyl ions (OH^-) and in converting

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Diagnosis

Continued

the CO_3 ions to HCO_3 ions. As a result, Pf alkalinity is a measure of the combined OH^- and CO_3 concentrations in the filtrate. The pH is a measure of the OH^- ion concentration. Consequently, the contribution of OH^- to the Pf alkalinity (POH) can be calculated from the pH measurement:

$$\text{POH} = 10(\text{pH}-12.3)$$

The millimoles per liter of CO_3 can be calculated as follows:

$$\text{CO}_3 = 20(\text{Pf}-\text{POH})$$

The Mf alkalinity is the cc's of 0.02 normal sulfuric acid required to reduce the pH of 1 cc of filtrate to 4.3. It is the sum of the Pf and the second titration where the pH is reduced from 8.3 to 4.3. In the second step, the acid is consumed in converting HCO_3 ions to CO_2 and water, and in reactions with organic acids and any other interfering ions that may exist in the filtrate. The lignosulfonate and lignite are the primary sources of interference to the test. Reaction of the acid with these organic acids cause the Mf to be greater than it would be otherwise. The HCO_3 ions that are converted to CO_2 and water, consist of the HCO_3 ions that were converted from CO_3 ions in the Pf titration and those that were originally in the filtrate. Consequently, Mf is the amount of acid necessary to neutralize the OH ions. convert CO_3 ions to HCO_3 ions, convert these HCO_3 ions,

Continued on next page

Diagnosis
Continued

and the HCO_3^- ions that were originally in the filtrate to CO_2 and water, and to react with the lignite and lignosulfonate. The ions that determine the magnitude of the alkalinites are shown in the table below:

Test	Measures
POH (Calculated from pH)	OH^-
P_f	$\text{OH}^- + \text{CO}_3^{=}$
M_f	$\text{OH} + \text{CO}_3^{=} + \text{HCO}_3^-$ converted from $\text{CO}_3^{=}$, + original HCO_3^- + interfering ions.

An increase in carbonates or an increase in interfering ion concentration. If a mud is untreated or if the concentrations of lignite and lignosulfonate have not been significantly increased, such an increase indicates an increase in carbonates. An estimate of the millimoles per liter of HCO_3^- can be determined as follows:

$$\text{HCO}_3^- = 20(M_f - 2P_f + \text{POH})$$

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Diagnosis

Continued

Remember that additions of lignite and lignosulfonate to a mud will cause this calculated HCO_3^- concentration to be greater than actual. The color change at the Mf titration endpoint is difficult to see and results in inaccuracies in the Mf value. This also will lead to an inaccurate calculation of HCO_3^- concentration. A pH meter can be used to accurately determine the endpoint at 4.3 and thus remove this source of inaccuracy.

An equilibrium exists between CO_3 and HCO_3^- concentrations depending on pH. The ratio of HCO_3^- to CO_3 concentrations can be calculated as follows:

$$\frac{\text{HCO}_3^-}{\text{CO}_3} = 10^{(10.1-\text{pH})}$$

Using this relationship and the CO_3 concentration calculated from pH and Pf measurements, the HCO_3^- concentration can be calculated without using the Mf measurement with its inherent inaccuracies. The millimoles per liter of HCO_3^- is calculated as follows:

$$\text{HCO}_3^- = P_f \times 10^{(11.4-\text{pH})}$$

In **Table 1**, $10^{(11.4-\text{pH})}$ has been calculated for various values of pH between 10 and 12. This leaves a simple multiplication to determine the HCO_3^- concentration. This table also lists the POH and simplified equations for calculating CO_3 concentrations at the various values of pH.

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Diagnosis

Continued

Although this method for calculating HCO_3 concentrations is probably more accurate than the one using Pf and Mf values, it also has limitations. The assumed ratio of HCO_3 to CO_3 as a function of pH is true only for fresh water solutions. As a consequence, the calculated values of HCO_3 concentration are increasingly too high as the salinity or the electrolyte content of the mud increases. However, changes in calculated HCO_3 concentrations from day to day should be relatively accurate if the salinity does not change. The calculation is also very dependent on accurate values of pH and Pf. This requires the use of an accurately calibrated pH meter rather than pH strip paper. The calculation becomes decreasingly less accurate at lower pH values, probably due to interference of dissolved CO_2 with the pH measurement. At pH less than 10, the calculation results in a higher HCO_3 concentrations than actual. In such a case, the pH of a sample of mud can be increased to over 10, the pH and Pf measured, and accurate HCO_3 and CO_3 concentrations calculated.

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Table 1
Carbonate-Bicarbonate Determination

pH	HCO₃ millimoles/l	CO₃ millimoles/l	P_{OH}
12.0	P _f	20(P _f -.5)	0.5
11.9	0.30 P _f	20(P _f -.4)	0.4
11.8	0.40 P _f	20(P _f -.3)	0.3
11.7	0.50 P _f	20(P _f -.25)	0.25
11.6	0.60 P _f	20(P _f -.2)	0.2
11.5	0.80 P _f	20(P _f -.16)	0.16
11.4	1.00 P _f	20(P _f -.13)	0.13
11.3	1.25 P _f	20(P _f -.1)	0.1
11.2	1.58 P _f	20(P _f -.08)	0.08
11.1	2.00 P _f	20(P _f -.06)	0.06
11.0	2.50 P _f	20(P _f -.05)	0.05
10.9	3.10 P _f	20(P _f -.04)	0.04
10.8	4.00 P _f	20(P _f -.03)	0.03
10.7	5.00 P _f	20(P _f -.025)	0.025
10.6	6.30 P _f	20(P _f -.02)	0.02
10.5	7.90 P _f	20(P _f -.016)	0.016
10.4	10.00 P _f	20(P _f -.013)	0.013
10.3	12.50 P _f	20(P _f -.01)	0.01
10.2	15.80 P _f	20(P _f -.008)	0.008
10.1	20.00 P _f	20(P _f -.006)	0.006
10.0	25.00 P _f	20(P _f -.005)	0.005

Example: pH = 10.5 P_f = 3
(HCO₃) = 7.9 x 3 = 23.7 millimoles/l
(CO₃) = 20 (3-.016) = 59.68 millimoles/l

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Diagnosis

Continued

There is another method for determining CO_3 and HCO_3 concentrations that involves the use of alkalinity measurements. It is the P_1 - P_2 Method described in API RP 13B, "Standard Procedure for Testing Drilling Fluids". It involves adding a measured amount of caustic solution to a diluted filtrate sample, adding barium chloride to precipitate the carbonates, and titrating to a pH 8.3 endpoint. This value is called P_1 . A blank sample of distilled water, caustic solution, and barium chloride is also titrated to obtain a P_2 value. P_2 - P_1 indicates the amount of OH that was used in converting HCO_3 to CO_2 . Therefore:

$$\text{HCO}_3 = 20(P_2 - P_1)$$

This method does not require an accurate pH measurement and is not influenced by the salinity of the mud. However, it does require two titrations and carefully measured additions of caustic solution. Since the calculation involves the difference in two titrations, it is susceptible to large errors.

Since all of these methods of carbonate analysis using alkalinity measurements have certain limitations, it would be wise to cross-check the results using at least two of the methods. Large discrepancies may mean inaccurate pH and alkalinity measurements and require rechecking these properties. In general, the pH, P_f Method will be the most accurate followed by the P_1 - P_2

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Diagnosis

Continued

Probably the most accurate method for determining carbonate content of a mud is with the Garrett Gas Train. The GGT was originally developed to determine sulfide content of a mud. By using a Drager tube designed to measure CO_2 , it can be used to determine carbonate content. In the test, acid is added to a filtrate sample, converting all of the carbonates to CO_2 . The CO_2 is collected and metered through the Drager tube. From the darkened length of the tube, the total carbonates ($\text{CO}_3 + \text{HCO}_3$) can be calculated.

The advantage of this method is that it is a direct measurement of carbonates and does not require pH and alkalinity measures and interpretations. However, it does not differentiate between CO_3 and HCO_3 . Since HCO_3 appears to be more harmful to mud properties than CO_3 , it may be desirable to estimate the HCO_3 concentration by use of the theoretical equilibrium that exists between CO_3 and HCO_3 at the pH of the mud. See **Table 2** below.

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Table 2 HCO₃⁻ Percent of Total Carbonates					
pH	%HCO ₃ ⁻	pH	%HCO ₃ ⁻	pH	%HCO ₃ ⁻
12.0	1.2	10.8	16.6	9.6	76.0
11.9	1.6	10.7	20.1	9.5	79.9
11.8	2.0	10.6	24.0	9.4	83.4
11.7	2.5	10.5	28.5	9.3	86.3
11.6	3.1	10.4	33.4	9.2	88.8
11.5	3.8	10.3	38.7	9.1	90.9
11.4	4.8	10.2	44.3	9.0	92.6
11.3	5.9	10.1	50.0	8.9	94.1
11.2	7.4	10.0	55.7	8.8	95.2
11.1	9.1	9.9	61.3	8.7	96.2
11.0	11.2	9.8	66.6	8.6	96.9
10.9	13.7	9.7	71.5	8.5	97.5

To convert mg/CO₃ to millimoles/l, divide by 60

Effect on Mud Properties

The effects of excessive soluble carbonates on mud properties are basically due to flocculation of the mud. This causes increases in the yield point, gel strength, and fluid loss. These effects are normally more pronounced downhole at elevated temperatures than at the surface. Consequently, the flow properties of the mud at the flow line will be increased over those at the suction. The first indication of a problem at the surface is usually an increase in the ten minute gel strength. The mud will look good as long as it is stirring, but will quickly form a fragile gel when sitting still. As the problem develops, the HTHP fluid loss will increase and eventually the yield point, initial gel strength, and API fluid loss will all increase. It should be remembered that the mud may be quite flocculated downhole before severe flocculation occurs at the surface. This can be observed in increased pressure required to initiate circulation.

In addition to causing flocculation, the carbonates may also convert calcium-base clays to sodium-base and thereby increase their yield. This will have the same effect on the mud properties as the addition of more bentonite, causing an overall increase in the flow properties. This effect will be more pronounced in mud having high concentrations of active drilled solids.

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Effect on Mud Properties

Continued

A carbonate problem is often accompanied by a reduction in pH or an increased consumption of caustic to maintain a constant pH. This is due to CO₂ being dissolved in the mud or from the process of extracting soluble carbonates from certain carbonate minerals in the barite. This effect will be most pronounced in the "bottoms-up" mud due to the increased temperature downhole.

The calcium content of a mud should decrease to zero as carbonates enter the mud due to precipitation as calcium carbonate. However, some amount of calcium is usually indicated by the total hardness titration even in the presence of high carbonate concentrations. A total hardness as high as 150 ppm may be measured in muds containing carbonates. This is probably due to calcium carried by the lignite and lignosulfonate as a complex ion or compound and not calcium ions in the filtrate that are free to react with the carbonate.

Treatment

The effects of flocculation caused by carbonates cannot be decreased by treatment with lignosulfonate or other deflocculants. Dilution is also usually of little or no benefit, especially if contaminated barite is the source of the problem. This necessitates treating the actual problem rather than its effects. Removal of carbonates involves addition of a soluble form of calcium to

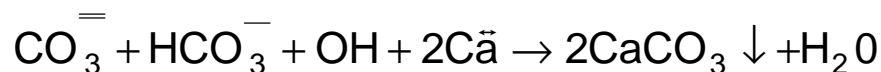
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Treatment

Continued

precipitate calcium carbonate. Usually lime or gypsum is used for this purpose.

Calcium precipitates CO_3 as calcium carbonate (CaCO_3). However, calcium will not precipitate HCO_3 unless it is first converted to CO_3 . If gypsum ($\text{CaSO}_4 \bullet 2\text{H}_2\text{O}$) is added to a mud that contains both CO_3 and HCO_3 , it will precipitate only the CO_3 , causing a reduction in pH and leaving in solution all of the original HCO_3 . Enough caustic must be added with the gypsum to convert all of the HCO_3 to CO_3 in order to precipitate both the CO_3 and HCO_3 .



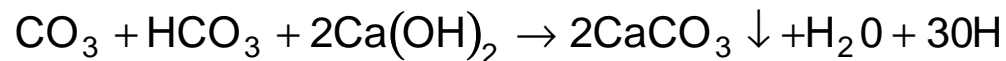
Required treatment:

0.014 ppb caustic per millimole/l of HCO_3

and

0.0602 ppb gypsum per millimole/l of ($\text{CO}_3 + \text{HCO}_3$)

If a mud containing carbonates has a pH that is lower than desired, lime can be added to precipitate carbonates and also increase the pH.

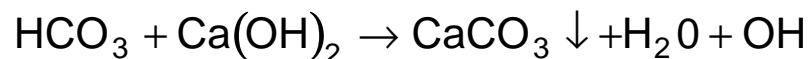


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Treatment

Continued

Notice that all the hydroxyl ions from the lime go into solution except those that are used in converting HCO_3 to CO_3 . In the reaction of lime with HCO_3 , one OH converts the HCO_3 to CO_3 , the calcium ion precipitates the CO_3 , and the remaining OH ion goes into solution to increase the pH. In the reaction of lime with CO_3 , both OH ions go into solution, increasing the pH very rapidly. For this reason, it is recommended that lime be used only to react with HCO_3 .



Required treatment:

0.0259 ppb lime per millimole/l of HCO_3

Even at this treatment level, the pH of the mud will increase as lime is added. Reaction of one lb./bbl of lime with HCO_3 will produce 0.54 lb./bbl of caustic. Normally, fresh lignosulfonate treatment is required after any precipitation takes place due to physical extraction of lignosulfonate from solution by the precipitant. Since lignosulfonate is an acid material, it will help in preventing the pH from increasing. Approximately 3 lb./bbl of lignosulfonate is required to neutralize the 0.5 lb./bbl of caustic resulting from 1 ppb of lime reacting with HCO_3 . Obviously, large amounts of lignosulfonate will be required to keep the pH from

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Treatment Continued

rising to undesirable levels if a large amount of lime is required. In this case, it would be better to switch to gypsum additions or to a combination of gypsum and lime. To maintain a constant pH while precipitating CO_3 and HCO_3 , the following treatment should be used:

0.01295 ppb lime per millimole/l HCO_3

0.0602 ppb gypsum per millimole/l($\text{CO}_3 + 1/2\text{HCO}_3$)

Additions of lime or gypsum to a mud should be made slowly. When additions are made too rapidly, the lime or calcium will react with the clay solids before they are used up in the carbonate reaction. The total calculated amounts should be added over several circulation cycles when large amounts are being added. Mud checks should be made between incremental additions and a new calculation of concentration of carbonates made as a safeguard against miscalculation.

Additions of lignite should be suspended while treating a carbonate problem since lignite will also react with the lime or gypsum and interfere with the treatment.

It is certainly advantageous to detect and treat a carbonate problem in the early stages, even before significant increases in flow properties occur. When 10 millimoles/l of HCO_3 are indicated,

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Treatment

Continued

0.25 lb./bbl of lime can be added without risk of harming the mud. If a carbonate problem is being caused by CO_2 that is generated by thermal degradation of lignosulfonate and lignite, small daily additions of lime will be required. This is very likely to occur in wells that have a bottom-hole temperature of over 300°F . The pH of the mud should be maintained between 11.0 and 11.5 so that most of the carbonates that do exist in the mud will be in the form of CO_3 rather than the more harmful HCO_3 . By maintaining the pH with lime and caustic, the total concentration of carbonates can be minimized. Overtreatment with lime will not occur as long as the pH does not exceed 11.5 since excess lime cannot exist at a pH of 11.5 or below. Under treatment with lime will result in an increasing trend in Mf-Pf. This will call for an increase in lime additions. Careful attention to preventing a carbonate problem is easier and considerably cheaper than the difficult task of eliminating a severe carbonate problem

Appendix A

PRESSURE CONTROL CALCULATIONS

Pressure Losses in Annulus in Laminar Flow

Pressure losses which occur in an annulus are due to the shear stress of the circulating fluid at the wall of the hole. The shear stress is a function of the shear rate at the wall and the viscosity of the mud at that shear rate.

In order to accurately calculate the pressure loss in a segment of an annulus of uniform geometry, we must know the shear rate at the wall and the shear stress at that specific shear rate.

We can express the shear rate in terms of RPM of a Fann V-G meter that will produce an equivalent shear rate.

$$\text{RPM} = \frac{1.409\bar{V}}{D_h - D_p}$$

Continued on next page

Pressure Losses
In Annulus In
Laminar Flow
Continued

Where:

\bar{V} = average annular velocity in ft/min

D_h = hole diameter in inches

D_p = pipe diameter in inches

$$\bar{V}, \text{ft / min} = \frac{\text{pump output, bbl / min}}{\text{Annular volume, bbl / ft}}$$

The equivalent shear rate in RPM is usually between 30 and 60 for most cases. Unfortunately, the standard V-G meters do not operate at these speeds. This necessitates plotting, on logarithmic paper, the V-G meter dial reading versus RPM at the available rotational speeds and extrapolating the resulting curve to the RPM of interest. A dial reading at the equivalent shear rate in the annulus can then be read from the curve. The pressure loss per 1000 feet can be calculated.

$$\text{Pressure loss, psi/1000 ft} = \frac{3.75\Theta}{D_h - D_p}$$

Where:.

Θ = Dial reading at calculated RPM

D_h = Hole diameter in inches

D_p = Pipe diameter in inches

Continued on next page

Pressure Losses in Annulus in Laminar Flow

Continued

NOTE: Sections of different geometry must be calculated separately.

This pressure loss equation is quite accurate for muds that have a power law index, n , above 0.6. For muds with n values below 0.6, ten percent should be added to the calculated pressure loss. Only highly gelled muds and some polymer muds will have a power law index below 0.6. For these muds, accurate predictions of downhole flow properties from surface measurements are so difficult that pressure loss calculations are going to be inaccurate anyway.

For muds that are stable at downhole temperatures, the flow properties measured at surface conditions will usually be greater than the downhole properties. This will lead to calculated pressure loss values which are higher than actual. If accurate predictions or actual measurements of the flow properties at downhole conditions can be obtained, these values should be used in the calculation

Equivalent Circulating Density

The equivalent circulating density of a mud is the sum of the mud density and the annular pressure drop converted to an equivalent density increase.

$$ECD = W_m + \frac{\Delta Pa}{(\text{Depth, ft})(0.052)}$$

Continued on next page

**Equivalent
Circulating Density**
Continued

Where:

ECD = equivalent circulating density, lb./gal

W_m = mud density, lb./gal

ΔP_a = annular pressure loss, psi

Depth = depth for which annular pressure loss was calculated

**Pressure Losses in
Annulus in
Turbulent Flow**

Flow in the annulus is usually laminar. However, with muds of low viscosity at high flow rates, turbulent flow can occur. The equation for calculating turbulent flow pressure losses in the annulus is:

$$\text{Pressure Loss, psi / 1000ft} = \frac{0.0765(PV)^{.18} W_m^{.82} Q^{1.82}}{(D_h - D_p)^3 (D_h + D_p)^{1.82}}$$

Where:

PV = plastic viscosity of the mud

W_m = mud density, lb./gal

Q = flow rate, gal/min

D_h = hole diameter, inches

D_p = pipe diameter, inches

Continued on next page

Pressure Losses in Annulus in Turbulent Flow
Continued

This equation is the same as used on the Reed Slide Rule to calculate annulus pressure losses.

If there is any doubt as to whether the flow in the annulus is laminar or turbulent, both the laminar and turbulent values should be calculated. The correct mode of flow is the one that gives the larger pressure loss.

Standpipe Pressure Method For Determining Pressure Losses in Annulus

The flow properties of muds are sensitive to temperature, contaminants, and long periods of quiescence. Any of these factors may cause the viscosity of the mud downhole to increase and lead to excessively high annular pressure losses.

Many times, the flow properties that we measure at the surface are not representative of the condition of the mud downhole. During a trip, the mud is exposed to temperatures higher than the circulating temperature and allowed to remain quiescent for several hours. Under these conditions, the mud will often become highly gelled and will retain a high viscosity until it is circulated to the surface and reconditioned. While making a trip or pulling up to make a connection, salt water can be swabbed into the wellbore and cause the mud to flocculate. Under such conditions, where the flow

Continued on next page

**Standpipe Pressure
Method For
Determining
Pressure Losses in
Annulus**
Continued

properties of the mud downhole are unknown, a direct calculation of the pressure loss in the annulus is highly inaccurate.

Another method, which does not require an accurate knowledge of the flow properties of the mud in the annulus, can be used to calculate the pressure loss in the annulus. We know that the total pressure at the standpipe is the sum of the pressure losses in each part of the circulating system. If we can measure the standpipe pressure and accurately calculate the pressure loss down the drill string and through the bit, we can determine the annular pressure loss by difference.

$$P_{sp} = P_{sc} + P_{dp} + P_{dc} + P_b + P_a$$

Where:

P_{sp}	=	total circulating pressure measured at standpipe
P_{sc}	=	
P_{dp}	=	pressure loss in surface equipment
P_{dc}	=	pressure loss down drill pipe
P_b	=	pressure loss down drill collars
P_a	=	pressure loss thru bit nozzles
		pressure loss in annulus

Continued on next page

**Standpipe Pressure
Method For
Determining
Pressure Losses in
Annulus**
Continued

By rearranging this equation, we can calculate the pressure loss in the annulus.

$$P_a = P_{sp} - (P_{sc} + P_{dp} + P_{dc} + P_b)$$

The Reed Slide Rule can be used to calculate P_{sc} , P_{dp} , P_{dc} , and P_b . As in all calculations, the results are only as good as the input data. An accurate flow rate and standpipe pressure are required. The following are necessary to obtain reliable data:

1. Calibrate pumps - do not assume an efficiency or use pump chart. Pump calibration must be made under operating conditions at several pump rates. The trip tank makes a good calibration tank.
2. Use low-pressure, recording-type pressure gauge. The Cameron type gauge is not adequate.
3. Check drill pipe and drill collar dimensions and nozzle sizes.
4. Pump for a sufficient time to obtain a stable pressure reading.
5. Make rate vs. pressure tests only when mud is stable and in good condition.

Continued on next page

**Standpipe Pressure
Method For
Determining
Pressure Losses in
Annulus**
Continued

This procedure has several advantages over the direct calculation of annular pressure loss. We know the inside measurements of the drill string with much more precision than hole size estimates. The mud is normally in turbulent flow inside the drill string. As a consequence, the flow properties of the mud have much less effect on pressure loss than in the annulus where the mud is in laminar flow. We also have a more accurate knowledge of flow properties of the mud we are pumping into the drill string than of the mud in the annulus.

Example:

Mud weight	=	14 lb./gal
Plastic viscosity	=	20 cp.
Surface Equipment	=	Case 3 on Reed Slide Rule
Drillpipe	=	14,000 ft with 3.78-inch ID
Drill collars	=	500 ft with 2.75-inch ID
Nozzles	=	three, $\frac{11}{32}$ inch
Standpipe Pressure	=	1300 psi
Flow Rate	=	200 gal/min

Continued on next page

**Standpipe Pressure
Method For
Determining
Pressure Losses in
Annulus
Continued**

$$\begin{array}{llll} \text{From Reed} & P_{sc} & = & 13 \text{ psi} \\ \text{Slide Rule:} & P_{dp} & = & 399 \text{ psi} \\ & P_{dc} & = & 67 \text{ psi} \\ & P_b & = & \underline{665 \text{ psi}} \\ & & & 1144 \text{ psi} \end{array}$$

$$P_a = 1300 - 1144 = \underline{\underline{156 \text{ psi}}}$$

**Use of the
Standpipe Pressure
Method to Prevent
Lost Returns**

Most lost returns can be prevented if the strength of the wellbore is known and if the pressure imposed on the wellbore is controlled below the pressure required to fracture the formation. If we can determine the pressure required to fracture the weakest point in the borehole by a leakoff test or accurate knowledge of the fracture gradient in the area, it becomes a matter of controlling the pressure imposed on the wellbore to prevent lost returns.

By monitoring the standpipe pressure and using the technique outlined above to calculate the pressure loss inside the drillstring and across the bit, we have a means of monitoring and controlling the pressure imposed on the borehole by circulation. This technique can also be used to limit the pressure required to initiate circulation to a level below the fracture pressure.

Continued on next page

**Use of the
Standpipe Pressure
Method to Prevent
Lost Returns**
Continued

The following steps are taken to establish a working chart that indicates the normal and maximum allowable standpipe pressure to break circulation at all circulating rates:

1. Measure the standpipe pressure required to break circulation. This pressure is an average and is determined on connections. Use a standpipe choke if available.
2. Measure the standpipe pressure at several circulating rates while drilling with the mud in good shape. About four different rates will be required to span the range from a slow rate to the maximum expected circulation rate. These measurements can and should be made while continuing the drilling operation.
3. Plot these data on graph paper to establish a normal operating curve. Assume a zero flow rate for the break circulation pressure. When the standpipe pressure differs from this curve, it probably indicates that a change in downhole mud properties has occurred. It may indicate trouble which should be corrected.
4. Calculate P_{sc} , P_{dp} , P_{dc} , and P_b with the Reed Slide Rule for each circulation rate.

Continued on next page

**Use of the
Standpipe Pressure
Method to Prevent
Lost Returns**
Continued

5. Determine the annular pressure loss that the hole will tolerate.

$$P_a \text{ max.} = (W_f - W_m)(.052 \times \text{depth})$$

W_f = Equivalent mud weight required to fracture or leak off test value

W_m = Current mud weight

6. Calculate the sum of ($P_a \text{ max.} + P_{sc} + P_{dp} + P_{dc} + P_b$) at each circulating rate. These pressures represent standpipe pressures which will cause the formation to fracture at each circulating rate. $P_a \text{ max.}$, represents the pressure that will cause the formation to fracture at zero circulation rate.
7. Subtract an appropriate safety factor (normally 50 to 100 psi) from these values and plot to establish the maximum allowable standpipe pressures at each flow rate. $P_a \text{ max.}$ minus the safety factor should be plotted at zero flow rate as a part of this curve. It represents the maximum pressure that should be used to initiate circulation. The technique can also be applied to diamond bit drilling. Pressure across the bit is obtained by difference in "on" and "off" bottom pressure at each different circulation rate.

Continued on next page

**Use of the
Standpipe Pressure
Method to Prevent
Lost Returns**
Continued

The need to update the data will depend on the individual well. In general, a pressure vs. Rate test should be run and a new curve drawn for each 500 feet of new hole and for each 0.5 lb./gal mud weight increase. The same applies when a new leak off test is conducted or when the bottom hole assembly or jet size is changed. The plot of standpipe pressure vs. Circulation rate should be posted in front of the driller and appropriate instructions given. The rate scale should be plotted in strokes per minute since most rig people think in these terms.

**The Standpipe
Choke**

Returns are often lost while attempting to establish circulation after trips and on connections. A standpipe choke provides a means of minimizing the pressure required to initiate circulation by allowing a gradual application of pump pressure. It consists of a hand-adjustable choke which is installed in the standpipe. Normally, a $\frac{3}{4}$ or 1-inch choke with a 5000-psi working pressure rating is used. The choke is piped in such a way that all the output from the pump can be by-passed to the mud pit with the choke open. Gradually closing the choke in steps while rotating the pipe will significantly reduce the pressure required to initiate circulation

After circulation is established, rotate and circulate 5 to 10 minutes before further closing the choke. Continue closing the choke in steps

Continued on next page

The Standpipe Choke

Continued

while maintaining the standpipe pressure below the maximum safe operating limit. The standpipe pressure should be closely monitored until after "bottoms up" have been obtained. If the standpipe pressure begins to increase, the pump rate should be decreased to maintain the pressure at or below the maximum allowable pressure. In some cases it may be necessary to partially open the choke until acceptable pressures are obtained.

Pressure Surges

Pressure surges are pressure gradients induced by movement of pipe in the annulus. They differ from pressure gradients produced by circulation only in that the flow of mud is produced by pipe motion rather than the pump.

If the flow rate of mud in the annulus produced by the pipe motion can be calculated, the resulting pressure gradient can be calculated using the circulating pressure loss equation.

There are at least two complicating problems. First, the flow rate of the mud in the annulus is difficult to determine if the mud can flow in the pipe as well as in the annulus. In this case, a part of the displaced volume flows in the pipe and the remainder in the annulus. Procedures for calculating the flow rates become very involved. Secondly, we are interested in making pressure surge calculation after the mud has remained quiescent for a period of time and

Continued on next page

Pressure Surges

Continued

gelation has taken place. Our knowledge of the flow properties downhole is usually very poor in this situation.

There are computer programs available which handle these problems relatively well. It would be advisable to use these programs when possible.

A quick estimate of pressure surges can be made if we make some simplifying assumptions. First, assume that the pipe is closed and no flow exists in the pipe. This assumption will yield calculated pressure gradients that are greater than actual if flow in the pipe does occur. Next, we need to estimate the maximum pipe velocity. We can assume that the maximum velocity is 1.5 times the average velocity. This assumption will lead to calculation of reasonably accurate peak pressure gradients. The peak flow rates in the annulus is then equal to the maximum pipe velocity times the sum of pipe displacement and capacity.

The pressure can then be calculated using this flow rate in the circulating pressure loss equation. The mud flow properties that should be used in the calculation are an educated guess. The properties measured at the surface will be less than those that exist downhole if a significant amount of gelation has taken place.

Continued on next page

Pressure Surges

Continued

When pipe is moving into the hole, the flow of mud is up the annulus just as in the case when the mud is circulated. The pressure surge adds to the total pressure at the bottom of the hole in the same manner as the circulating pressure drop. When the pipe is moving out of the hole, the flow of mud is down the annulus. This creates a negative pressure surge or swab pressure. In this case the induced pressure gradient subtracts from hydrostatic pressure.

To further complicate the swab situation, the fluid level falls in the annulus as pipe is pulled from the hole. This will further reduce the hydrostatic pressure downhole unless the hole is filled from the top. This is absolutely essential.

Another precaution which should be noted is: The pump should not be running at any time the pipe is being run into the hole. In this case the flow due to pipe movement adds to the circulating flow and causes extra high flowing pressure drops.

Pressure surge calculations are inherently inaccurate and should be used only as a guide. They will point out critical situations where care should be used to maintain slow pipe-running speeds.

Density Increase

From Drilled Solids

Influx

When solids are introduced into the mud at the bit, the density of the mud is increased. During periods of fast drilling, this increase in density of the mud in the annulus can be significant and can contribute to lost circulation.

Continued on next page

**Density Increase
From Drilled Solids
Influx**

Continued

An estimate of the mud density in the annulus can be calculated with the following equation:

$$\text{Mud Density in Annulus} = \frac{W_m(Q) + 20(ROP)(V_h)}{Q + (ROP)(V_h)}$$

Where:

W_m = Mud weight at the suction, lb./gal

Q = Mud circulation rate, bbl/min.

ROP = Drilling rate, ft/min.

V_h = Hole capacity, bbl/ft.

The constant, 20, in the equation assumes a bulk density of the formation solids of 2.4 g/cc. If the actual bulk density is known, a more accurate constant can be calculated and used in the equation.

Constant = 8.34 (Bulk Density)

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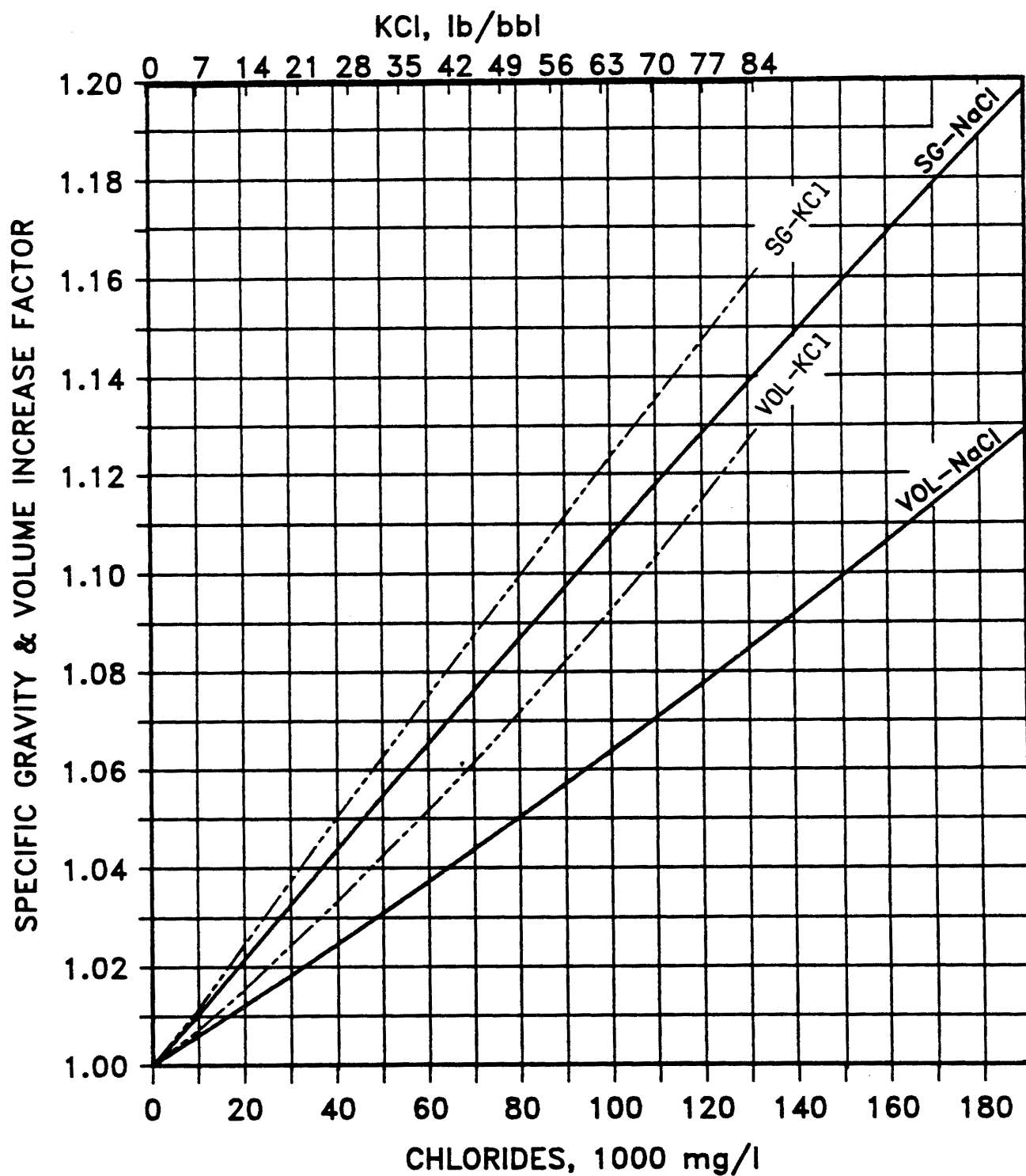
<p style="text-align: center;">PRESSURE GRADIENT, PSI/FT <i>TENTHS OF POUNDS OF GALLON</i></p>										
Mud Density lb./gal	0	1	2	3	4	5	6	7	8	9
8	.4156	.4208	.4260	.4312	.4364	.4416	.4468	.4519	.4571	.4623
9	.4675	.4727	.4779	.4831	.4883	.4935	.4987	.5039	.5091	.5143
10	.5195	.5247	.5299	.5350	.5403	.5455	.5506	.5558	.5610	.5662
11	.5714	.5766	.5818	.5870	.5922	.5974	.6026	.6078	.6130	.6182
12	.6234	.6285	.6338	.6390	.6442	.6493	.6545	.6597	.6649	.6701
13	.6753	.6805	.6857	.6909	.6961	.7013	.7065	.7117	.7169	.7221
14	.7273	.7325	.7377	.7429	.7481	.7532	.7584	.7636	.7688	.7740
15	.7792	.7844	.7896	.7948	.8000	.8052	.8104	.8156	.8208	.8260
16	.8312	.8364	.8416	.8468	.8519	.8571	.8623	.8675	.8727	.8779
17	.8831	.8883	.8935	.8987	.9039	.9091	.9143	.9195	.9247	.9299
18	.9351	.9403	.9455	.9506	.9558	.9610	.9662	.9714	.9766	.9818
19	.9870	.9922	.9974	1.0026	1.0078	1.0130	1.0182	1.0234	1.0286	1.0338

Pressure Gradient, psi/ft = Mud Weight, lb./gal x 0.052

Pressure, psi = Pressure Gradient, psi/ft x Depth, ft

$$\text{Equivalent Mud Density} = \frac{\text{Pressure, psi}}{\text{Depth} \times 0.052}$$

SODIUM & POTASSIUM CHLORIDE SPECIFIC GRAVITY & VOLUME INCREASE



Appendix B

SOLIDS ANALYSIS AND CONTROL

Mud Solids Analysis

The primary source of control of rheological and filtration properties of a mud is the control of amount and type of solids in the mud. In order to properly control the solids, it is necessary to know the amount of each of the various types of solids contained in the mud. An estimate of the amounts of these solids can be made from tests that are normally performed on a mud.

If we assume that all the suspended solids in a mud have a specific gravity of either 4.25 (barite) or 2.6 (drilled solids and bentonite), we can make measurements that will allow us to calculate the relative amounts of each of these two types of solids. For this calculation, we need an accurate mud density, retort analysis, and chloride determination.

Continued on next page

Mud Solids Analysis

Continued

The general equation for calculating volume per cent low-gravity solids is:

$$\%L.G. = \frac{425 - \%W_a(4.25 - S_w) - \%O(4.25 - S_o) - 100 \frac{\text{Mud wt.}}{8.3}}{4.25 - 2.6}$$

Where:

S_w = Specific gravity of water

S_o = Specific gravity of oil

In the case of a saltwater mud, the % water used in this equation should be the actual % saltwater in the mud and not the % water from the retort. The water collected from a retort is distilled and is less in volume than when it contains dissolved salt. The actual specific gravity of the salt water should be used in the equation. The effect of salinity on specific gravity and volume is shown on the following page.

The % oil as measured with the retort can be used in this equation. Diesel oil normally has a specific gravity of about 0.84.

The number 2.6 in the equation is the assumed specific gravity of the low-gravity solids. If the exact specific gravity of these solids is known, the correct value should be used in the equation. For

Continued on next page

Mud Solids Analysis Continued

example, limestone solids will have a specific gravity of about 2.8. If the solids are predominantly limestone, 2.8 should be used in the equation.

If a mud is made with fresh water and contains no oil, the general equation can be simplified to the following:

$$\% \text{ L.G.} = 60.6 + 1.97 (\% \text{ solids}) - 7.3 (\text{Mud Wt.})$$

We also need to know the relative amounts of high yield bentonite and low quality drilled solids that make up the low gravity fraction. Since different types of solids have different cation exchange capacities, it is possible to differentiate between bentonite and other low gravity solids with the methylene blue test. The methylene blue capacity of a mud is the average cation exchange capacity of the solids in the mud. If we know the cation exchange capacity of bentonite and of the drilled solids, we can calculate how much of each is present in the low gravity fraction of the mud.

On an average, the low-quality shale solids have about one ninth of the exchange capacity of Wyoming bentonite. With this assumption we can calculate the volume percent bentonite with the following equation:

Continued on next page

Mud Solids Analysis

Continued

$$\% \text{ Bentonite} = \frac{\text{CEC, lb / bbl} - \% \text{ L. G.}}{8}$$

and

$$\% \text{ Drilled Solids} + \% \text{ L.G.} - \% \text{ Bentonite}$$

Volume percent of a 2.6 specific gravity material can be converted to lb./bbl by multiplying by 9.1. Volume percent barite (specific gravity 4.25) can be converted to lb./bbl by multiplying by 14.875.

The large fold-out chart presents graphical solutions to the preceding equations. Chart 1 in the upper right-hand portion solves the simplified equation, assuming fresh water and no oil.

If the mud contains salt, the indicated percent low-gravity solids will be higher than the mud actually contains. A correction for this discrepancy can be obtained from the Chart 3 in the lower left-hand corner. It indicates the percent low-gravity solids that should be subtracted from the value indicated by the first chart.

If the mud contains oil, Chart 4 at the bottom of the fold-out indicates the percent low-gravity solids that should be subtracted from the original value to correct for the presence of the oil.

When the corrected low-gravity solids content has been determined, the percent Bentonite can be estimated from Chart 2 in the upper left-hand corner of the fold-out.

Continued on next page

Mud Solids Analysis Continued

The total percent suspended solids can be calculated by subtracting the percent low-gravity solids correction values from Charts 3 and 4 from the percent solids calculated from the retort.

In unweighted muds, that contain only low-gravity solids, the determination of volume percent solids is greatly simplified. Only the mud density, salinity, and oil content are needed for this calculation. The following is the general equation for calculating percent solids of an unweighted mud:

$$\% \text{Solids} = \frac{100 \left(\frac{\text{Mud wt.}}{8.3} - S_w \right)}{2.6 - S_w} + \frac{\% \text{Oil} \left(\frac{S_w - S_o}{2.6 - S_w} \right)}{2.6 - S_w}$$

This calculation gives a more accurate determination of percent solids than can be obtained with a mud retort. The only reason for a retort analysis on unweighted muds is to obtain the percent oil. If the mud contains no salt or oil, the general equation reduces to:

$$\% \text{ Solids} = 7.5 (\text{Mud Wt.}) - 62.2$$

Another chart is provided for solving the general equation for unweighted muds. It assumes low-gravity solids of 2.6 specific gravity and oil of 0.84 specific gravity. To use this chart, find the intersection of mud density and chloride content and read the % solids content at the left margin. If the mud contains oil, a correction

Continued on next page

**Mud Solids
Analysis**
Continued

must be made. On the small chart at the top, find the intersection of chloride content and percent oil and read additional percent solids at the left.

These additional solids must be added to the original percent solids value to obtain the correct value of total percent solids. If the percent bentonite is desired, it can be determined on the large fold-out chart as before.

Chart 1

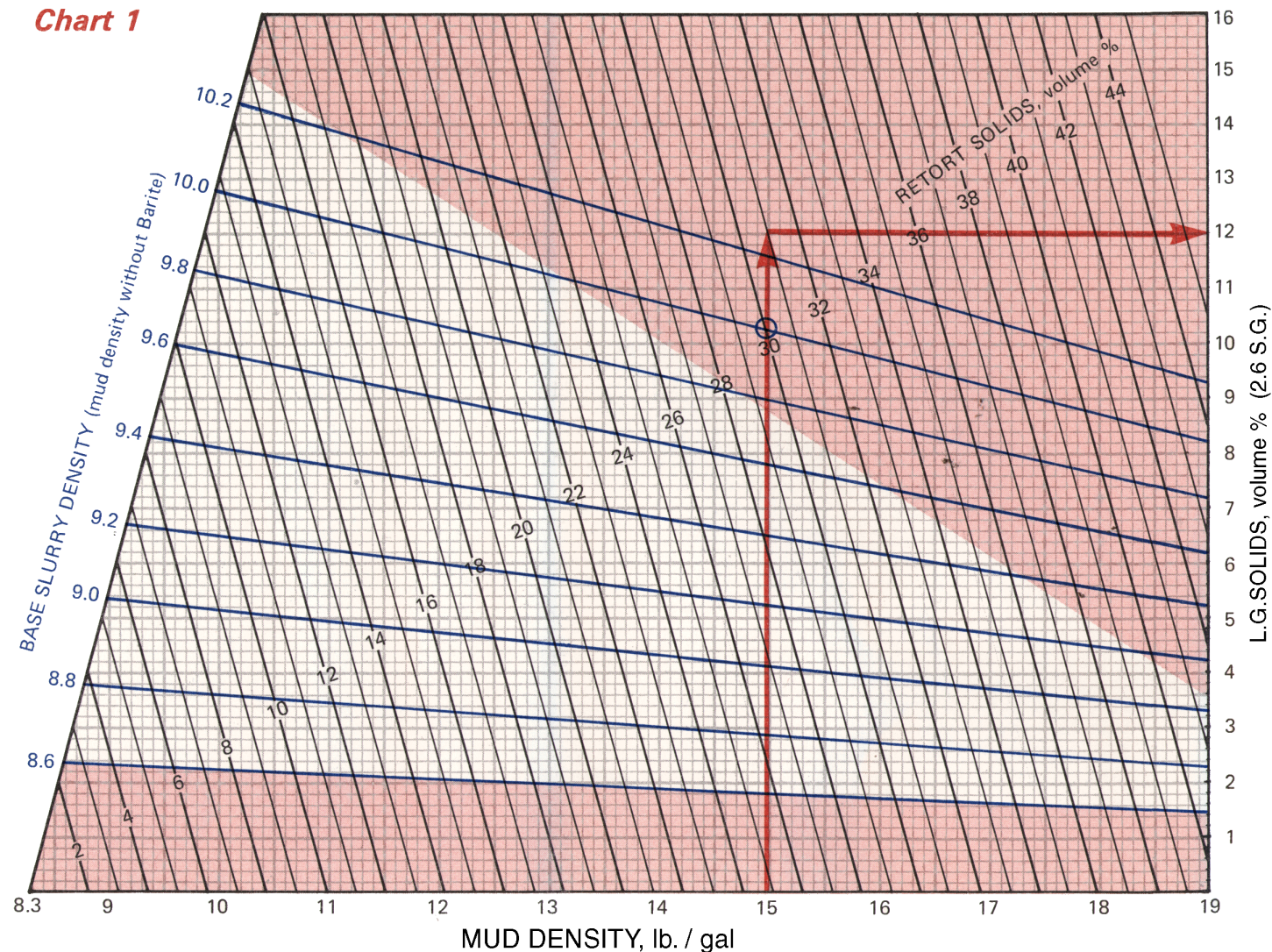
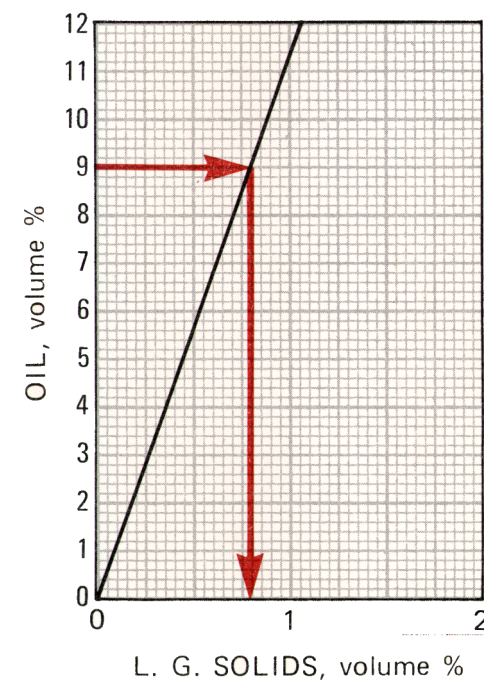


Chart 3



BASE SLURRY DENSITY
Assume a 15 lb / gal Freshwater mud containing 30% Solids. This point on Chart 1 falls on a blue line labeled 10.0lb / gal Which would be the density of the mud if contained no barite.

Chart 4

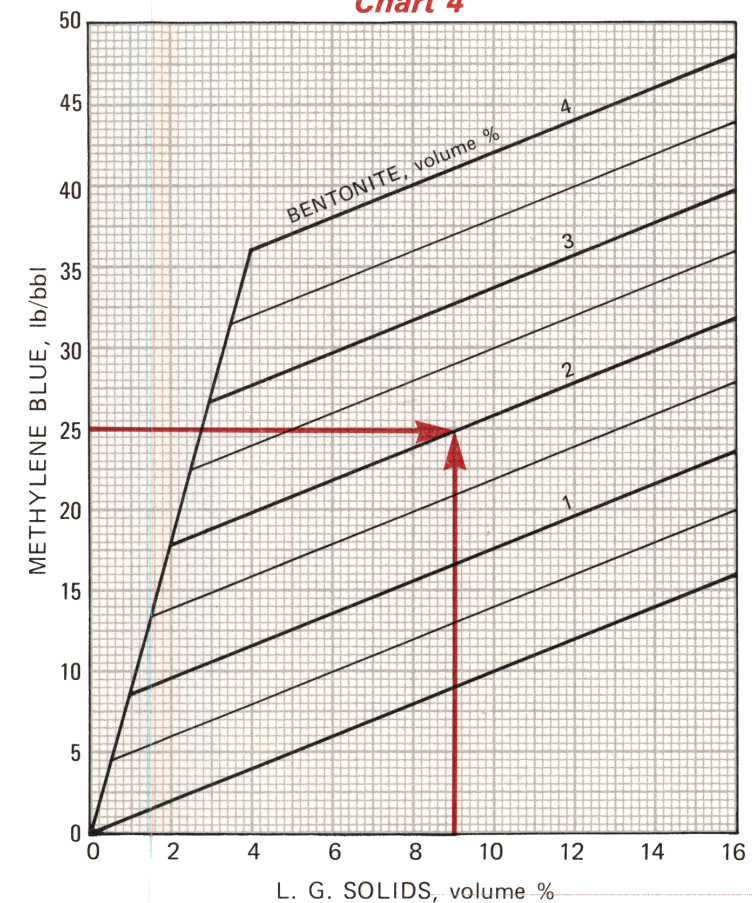
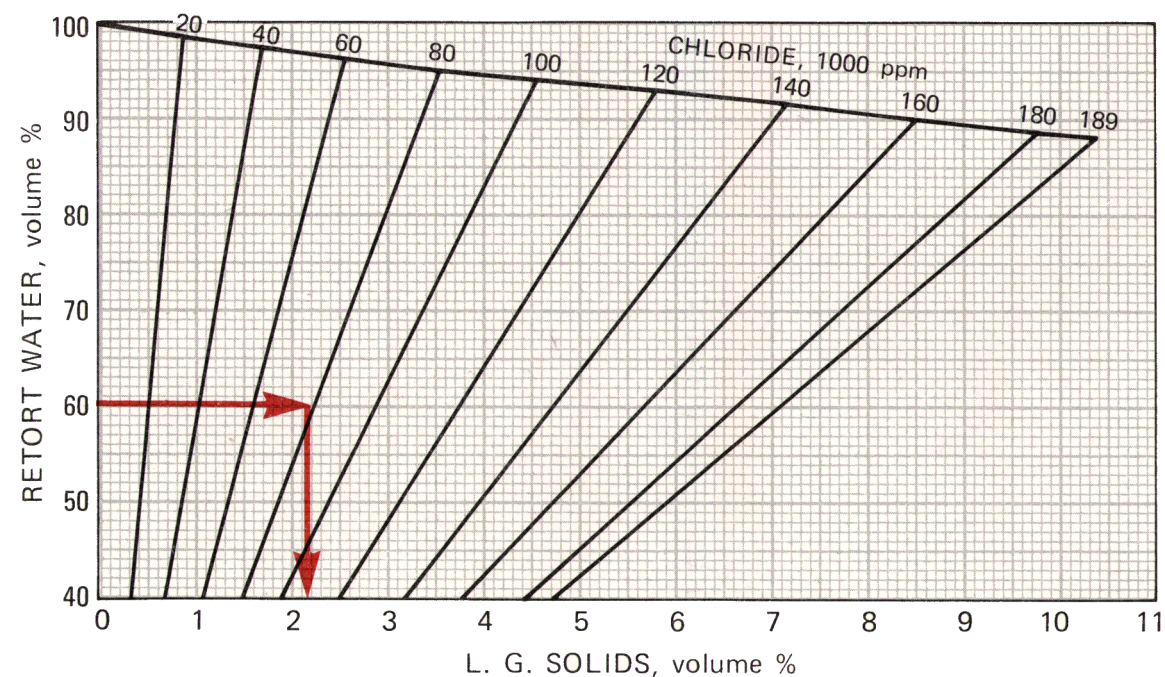


Chart 2



SOLIDS ANALYSIS EXAMPLE

Mud Weight.....	15 lb/gal	Mud Retort Water	60%
Chlorides.....	80,000	Mud Retort Oil	9%
Methylene Blue	25 lb / gal	Mud retort Solids	31%

Enter Chart 1 at 15 lb / gal Mud Density and find intersection with 31% Retort Solids. Read across to 12% L.G. Solids.

Enter Chart 2 at 60% Retort Water and find intersection with 80,000 ppm Chlorides. Read down to 2.2% L.G. Solids.

Enter Chart 3 at 9% Oil and read down from intersection to 0.8% L.G. Solids.

TO CORRECT FOR PRESENCE OF SALT AND OIL, subtract the L.G. Solids found in Charts 2 and 3 from that found in Chart 1. $12\% - 2.2\% - 0.8\% = 9\%$ L.G. Solids

Enter Chart 4 at 25 lb / bbl Methylene Blue and 9% L.G. Solids. Read intersection - 2% Bentonite.

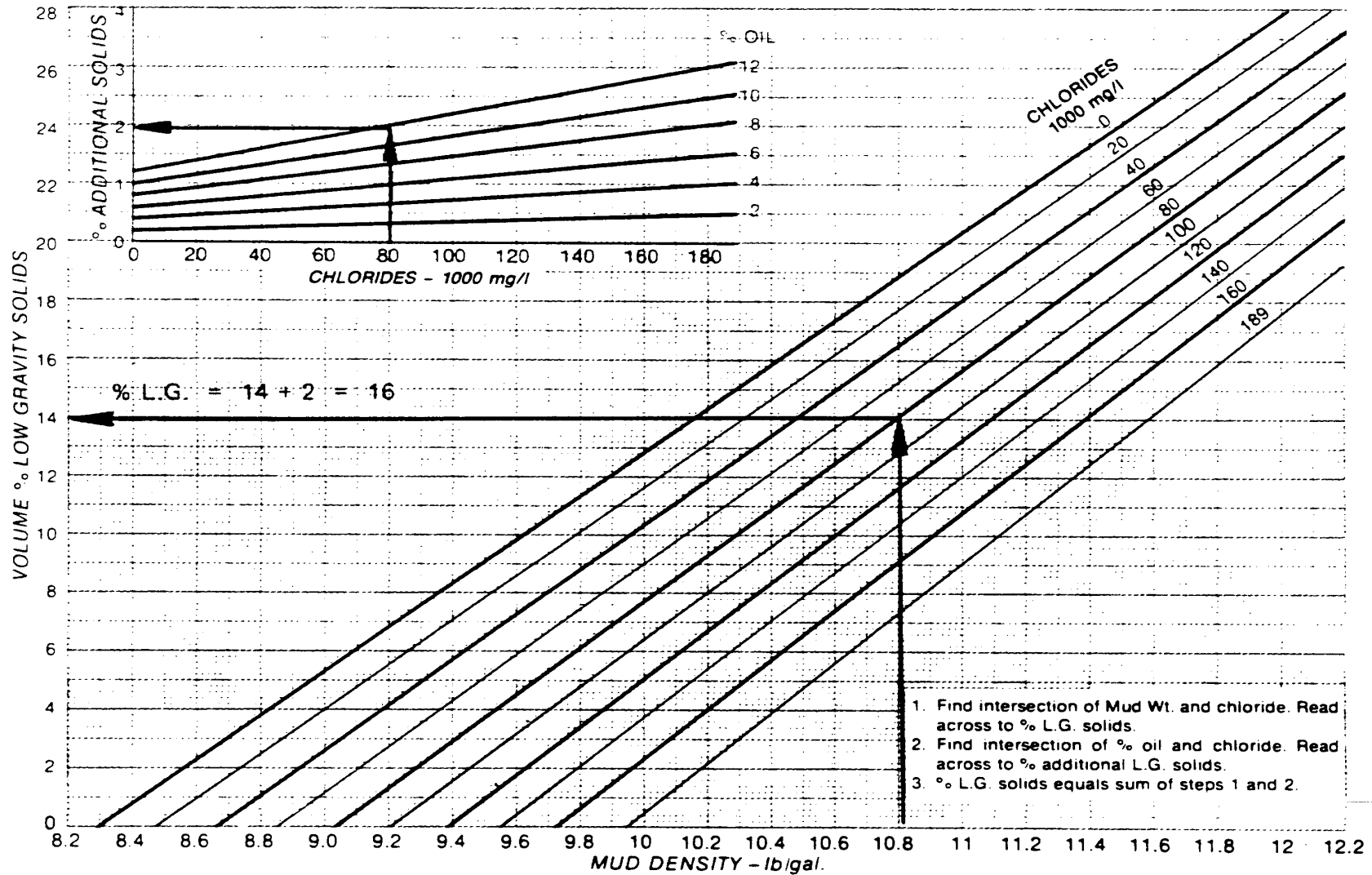
$9\% \text{ L.G. Solids} - 2\% \text{ Bentonite} = 7\% \text{ DRILLED SOLIDS}$

$31\% - 2.2\% - 0.8\% = 28\% \text{ TOTAL SUSPENDED SOLIDS}$

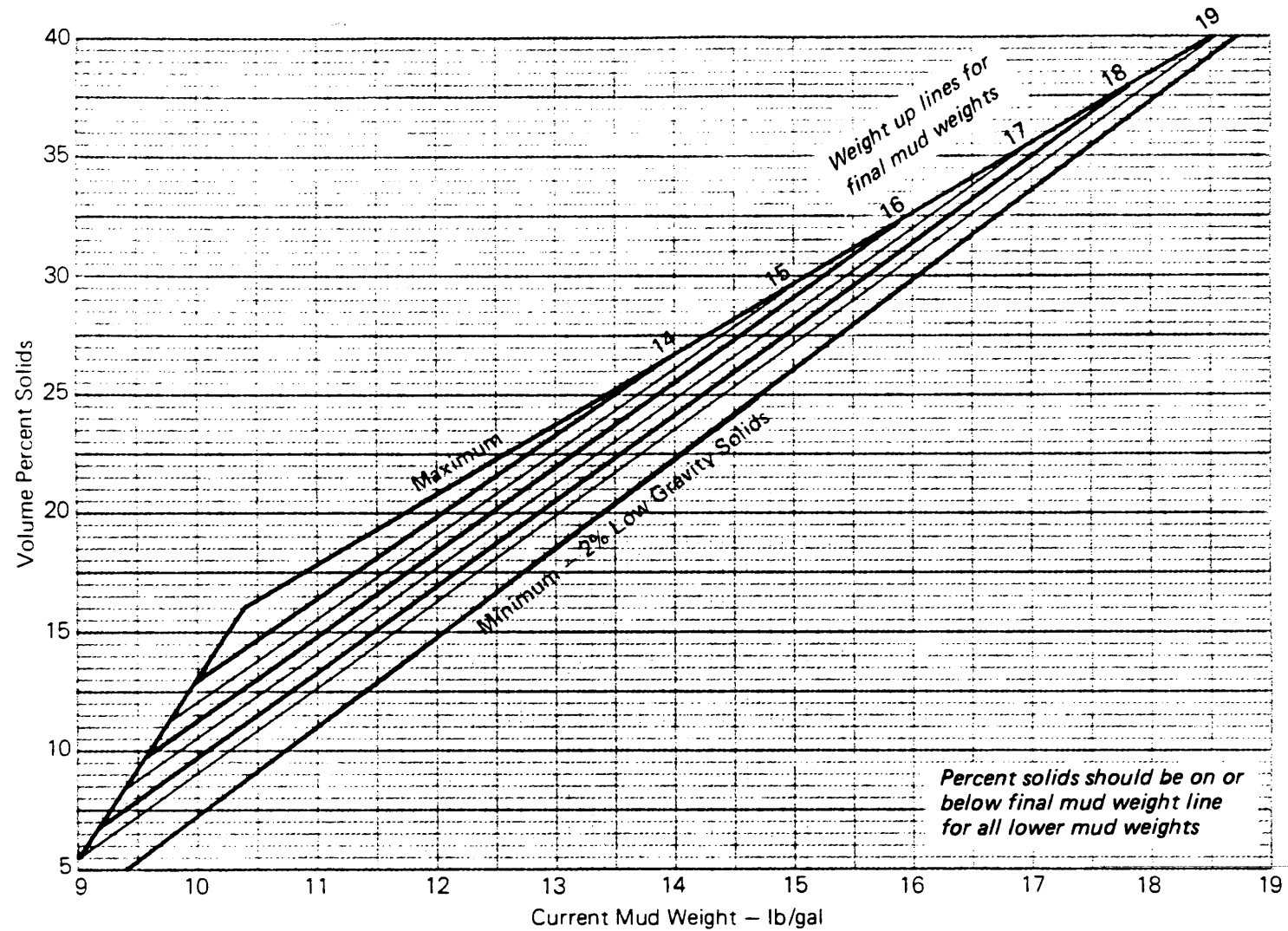
$28\% - 9\% = 19\% \text{ BARITE}$

$19\% \times 14.875 = 282.6 \text{ lb / bbl BARITE}$

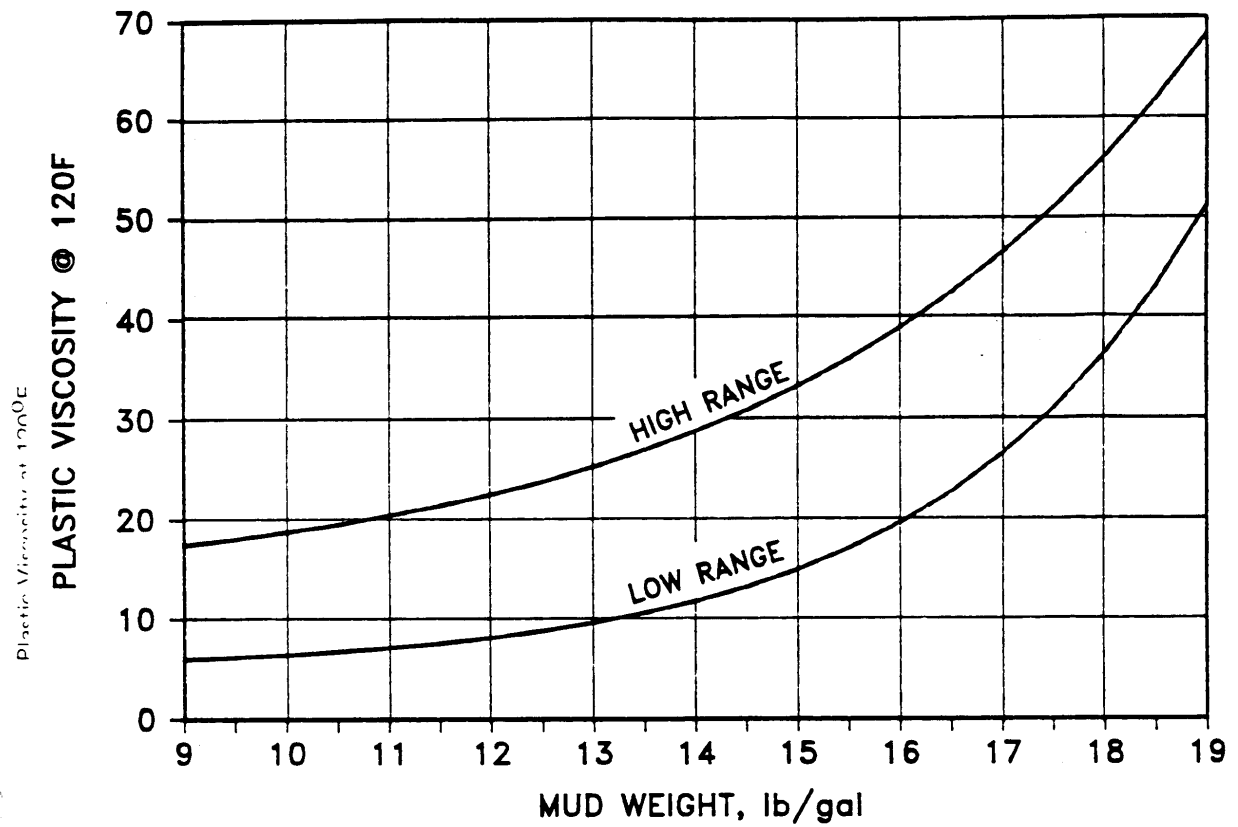
Solids Determination for Unweighted Muds



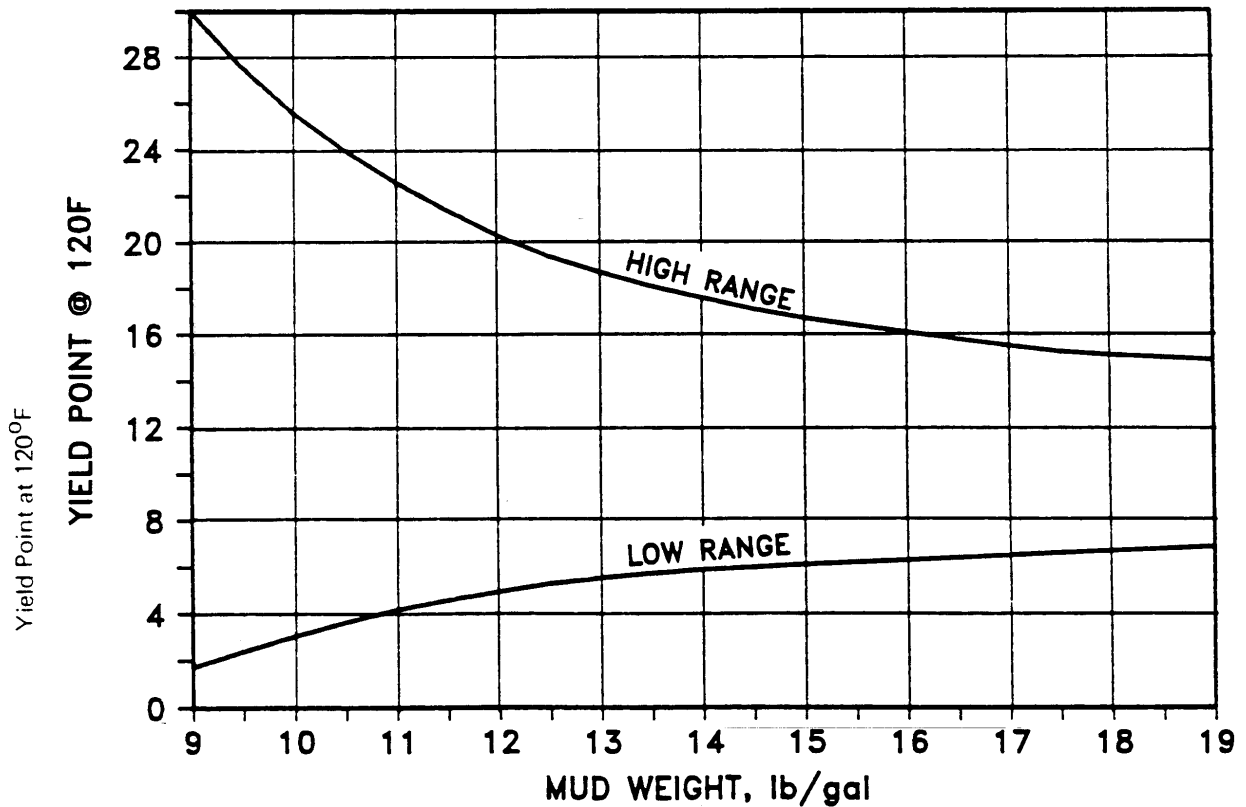
Recommended Range of Solids Content



PV-RANGE FOR BARITE MUDS



YIELD POINT RANGE



Materials Requirements while Centrifuging

When the underflow is returned to the active system, it must be rebuilt into mud of the proper density containing the desired amount of bentonite and chemical. Since some of the barite and drilled solids are discarded in the overflow, the volume of mud reclaimed from the underflow will be less than the volume of mud processed. A small additional volume of new mud must be built in order to maintain the volume of the mud system constant.

In order to centrifuge a barrel of mud and reconstruct a barrel of new mud with the desired properties, it is necessary that additions of barite, bentonite, chemical, and water are carefully matched to the centrifuge operation. Using a material-balance calculation, the centrifuging process can be mathematically simulated and the materials requirements determined.

The following input data are required in this calculation:

1. Density of feed mud, W_m lb./gal
2. Density of overflow, W_{of} lb./gal
3. Density of underflow, W_{uf} lb./gal
4. Mud feed rate to centrifuge, f_m gal/min

Continued on next page

**Materials
Requirements while
Centrifuging**
Continued

5. Dilution water feed rate to centrifuge, f_w gal/min
6. Required bentonite content of mud, lb./bbl
7. Required chemical content of mud, lb./bbl

$$\text{Dilution factor, } D = \frac{\text{dilution water feed rate}}{\text{mud feed rate}}$$

The following material balance can be written to determine the volume of underflow, V_{uf} , resulting from centrifuging one barrel of mud:

$$1. \quad V_{uf} = \frac{W_m}{W_{uf}} \frac{8.3(D) W_{of}(1 - D)}{W_{of}} \quad \text{bbl underflow / bbl feed mud}$$

Next, we need to know the composition of the underflow in order to determine the amount of barite, bentonite, chemical, and water which must be added to build a barrel of new mud. The underflow consists of the diluted feed mud plus the barite that settled into it. If we assume perfect mixing of the feed mud and dilution water in the centrifuge, then the diluted feed mud in the underflow should consist of feed mud and dilution water in the same ratio as they existed going into the centrifuge. We can now calculate the volume fractions of feed mud (C_m), dilution water (C_w), and settled barite (C_b) in the underflow.

Continued on next page

Materials
Requirements while
Centrifuging
Continued

$$2. \quad C_m = \frac{4.25 - \frac{W_{uf}}{8.3}}{4.25 + D(4.25 - \text{sp. gr. wa}) - \frac{W_m}{8.3}}$$

The specific gravity of water can be assumed to be 1.0 unless salt water is used as dilution water. In the case the correct specific gravity should be used.

$$3. \quad C_w = D(C_m)$$

$$4. \quad C_b = 1 - C_m - C_w$$

Knowing the volume of underflow per barrel of mud centrifuged and the volume fractions of barite, while mud, and dilution water that comprise the underflow, we can calculate the volume of these components recovered from one barrel of feed mud:

$$5. \quad V_m = C_m V_{uf} = \text{bbl whole mud in underflow/bbl feed mud}$$

$$6. \quad V_w = C_w V_{uf} = \text{bbl dilution water in underflow/bbl feed mud}$$

$$7. \quad V_b = C_b V_{uf} = \text{bbl settled barite in underflow/bbl feed mud}$$

Since V_m is already mud of the required density, we need to build $1 - V_m$ bbl of mud using V_w , V_b and additional barite, bentonite, chemical, and water. The percent barite, bentonite, and water of the mud we wish to build can be determined from a solids analysis chart or can be calculated.

Continued on next page

**Materials
Requirements while
Centrifuging**
Continued

$$8. \quad \% \text{ Bentonite in mud} = \frac{\text{lb / bbl bentonite desired}}{9}$$

Enter solids analysis chart at desired mud weight and read total solids content at desired % bentonite.

$$9. \quad \% \text{ Barite} = \% \text{ total solids} - \% \text{ bentonite barite, lb./bbl} = \% \text{ barite (14.875)}$$

$$10. \quad \% \text{ Water} = 100 - \% \text{ total solids}$$

$$11. \quad \text{lb. Required bentonite per bbl feed mud} = (\text{lb./bbl bentonite desired}) (1 - V_m)$$

$$12. \quad \text{bbl required water per bbl feed mud} = \frac{\% \text{water}}{100} (1 - V_m) - V_w$$

$$13. \quad \text{lb. Required barite per bbl feed mud} = (\% \text{ barite})(14.867)(1 - V_m) - V_b(1487.5)$$

$$14. \quad \text{lb. Required chemical per bbl feed mud} = (\text{lb./bbl chemical desired})(1 - V_m)$$

The materials requirements determined in Eq. 11, 12, 13, and 14 are based on one barrel of feed mud. The requirements per hour of centrifuge operation can be determined by multiplying by the barrels of mud centrifuged per hour.

Continued on next page

**Materials
Requirements while
Centrifuging**

Continued

$$15. \text{ bbl mud centrifuged per hour} = (\text{mud feed rate, gpm})(1.4286)$$

Material requirements per hour of centrifuging:

$$16. \text{ Bentonite lb./hr} = (\text{Eq. 11})(\text{Eq. 15})$$

$$17. \text{ Water bbl/hr} = (\text{Eq. 12})(\text{Eq. 15})$$

$$18. \text{ Barite lb./hr} = (\text{Eq. 13})(\text{Eq. 15})$$

$$19. \text{ Chemical lb./hr} = (\text{Eq. 14})(\text{Eq. 15})$$

The materials cost per hour can be calculated by multiplying the unit cost of each material by the amount used per hour. The sum of these costs, multiplied by the numbers of hours of centrifuge use per day, plus the centrifuge rental cost gives the daily cost of centrifuge operation.

If the numbers of pounds of drilled solids discarded by the centrifuge per day could be determined, the removal cost per pound could be calculated. However, there is no good way to determine the pounds of drilled solids discarded. If you assume that between 30 and 60 percent of the drilled solids are being removed from the mud processed by the centrifuge, the approximate amount of drilled solids removed can be calculated:

Continued on next page

**Requirements while
Centrifuging**
Continued

$$\text{Drilled solids removed lb./day} = \left(\frac{\% \text{ removed}}{100} \right) \left(\frac{\% \text{ in mud}}{100} \right) (\text{bbl centrifuged / day}) 900$$

Example Problem

The following data were obtained while centrifuging a mud:

1. Density of Feed Mud = 16.2 lb./gal
2. Density of Overflow = 9.3 lb./gal
3. Density of Underflow = 23.4 lb./gal
4. Mud feed rate to centrifuge = 16.53 gal/min
5. Water feed rate to centrifuge = 10.57 gal/min
6. Required bentonite content = 22.5 lb./bbl
7. Required lignosulfonate content = 6 lb./bb

$$D = \frac{10.57}{16.53} = 0.639$$

Continued on next page

Example Problem

Continued

1. $V_{uf} + \frac{16.2 + 8.3(.639) - 9.3(1.639)}{23.4 - 9.3} = \mathbf{0.444 \text{ bbl/bbl mud}}$
2. $C_m = \frac{4.25 - \frac{23.4}{8.3}}{4.25 + .639(3.25) - \frac{16.2}{8.3}} = \mathbf{0.327}$
3. $C_w = 0.639(0.327) = \mathbf{0.209}$
4. $C_b = 1 - 0.327 - 0.209 = \mathbf{0.464}$
5. $V_m = 0.327(0.444) = \mathbf{0.145 \text{ bbl/bbl feed mud}}$
6. $V_w = 0.209(0.444) = \mathbf{0.093 \text{ bbl/bbl feed mud}}$
7. $V_b = 0.464 (0.444) = \mathbf{0.206 \text{ bbl/bbl feed mud}}$
8. $\frac{22.5}{9} = \mathbf{2.5\% \text{ bentonite}}$
9. $30.5 - 2.5 = \mathbf{28\% \text{ barite}}$ $28 \times 14.875 = \mathbf{416.5 \text{ lb./bbl, barite}}$
10. $100 - 30.5 = \mathbf{69.5\% \text{ water}}$
11. $22.5(1 - 0.145) = 22.5(0.855) = \mathbf{19.24 \text{ lb. bentonite}}$

Continued on next page

Example Problem

Continued

$$12. \frac{69.5}{100}(0.855) - 0.093 = \mathbf{0.501 \text{ bbl water}}$$

$$13. 416.5(0.855) - 0.206(1487.5) = \mathbf{49.68 \text{ lb. barite}}$$

$$14. 6(0.855) = \mathbf{5.13 \text{ lb. lignosulfonate}}$$

$$15. 16.53(1.4286) = \mathbf{23.61 \text{ bbl/hr}}$$

$$16. 19.24(23.61) = \mathbf{454 \text{ lb./hr bentonite}}$$

$$17. 0.501(23.61) = \mathbf{11.8 \text{ bbl/hr} = 496 \text{ gal/hr water}}$$

$$18. 49.68(23.61) = \mathbf{1173 \text{ lb./hr barite}}$$

$$19. 5.13(23.61) = \mathbf{121 \text{ lb./hr lignosulfonate}}$$

	Cost/lb.	Cost/hr Centrifuging
Barite	\$0.0365	\$42.81
Bentonite	0.0374	16.98
Lignosulfonate	0.255	<u>30.86</u>
		\$90.65

Continued on next page

Example Problem
Continued

Assume 8 hours centrifuging per day and \$85/day rental cost on centrifuge:

$$90.65 \times 8 = \$725$$

$$\underline{\quad 85 \quad}$$

\$810/day centrifuging cost

Assume that the centrifuge removed half of the drilled solids in the mud and the mud contain 4 percent drilled solids. In other word, the centrifuge removed 2 percent of the drilled solids in the mud that was processed.

$$23.61 \text{ bbl/hr} \times 8 \text{ hr} = 188.88 \text{ bbl of mud processed}$$

$$0.02 \times 188.88 = 3.78 \text{ bbl of drilled solids}$$

$$3.78 \times 900 = 3400 \text{ lb. Of drilled solids}$$

$$\frac{\$810}{3400 \text{ lb}} = \mathbf{\$0.24/\text{lb of drilled solids removed.}}$$

From **Figure 2** in the Solids Control Section, the dilution cost for maintaining a 16.2 lb./gal mud at 4 percent drilled solids level would be \$0.44/lb of drilled solids incorporated in new mud volume. This represents an 83% increase in mud maintenance cost over centrifuging.

Continued on next page

Example Problem Continued

If the centrifuge had removed only 27% of the drilled solids in the mud, it would result in a breakdown cost with dilution.

Desander and Desilter Performance Calculations

When desanding or desilting an unweighted mud, it is possible to determine the quantity of solids being removed by measuring the underflow density and rate of discharge. The pounds of solids removed per hour can be calculated as follows:

$$\text{Solids Discharge, lb./hr} = \frac{1460(\text{underflow density} - 8.3)}{\text{underflow discharge rate, sec/ qt.}}$$

To determine the underflow discharge rate and density, the following procedure is used:

1. Measure the time in seconds required to catch a quart sample from each cone. Use a mud cup and stop watch.
2. Measure the density of the underflow (lb./gal) from each cone with a mud balance.

Calculate the solids discharge rate for each cone and sum to find the total.

The water discharge rate from the underflow can also be calculated. This number represents the volume of water that should be added to the mud to maintain constant volume. The gallons of water removed per hour can be calculated as follows:

Continued on next page

Desander and Desilter

Performance

Calculations

Continued

$$\text{Water Discharge Rate, gal/hr} = \frac{67.26(21.68 - \text{underflow density})}{\text{underflow discharge rate, sec/ qt}}$$

The cost per pound of solids removed is equal to:

$$\text{Cost, \$/lb.} = \frac{R + C}{S}$$

Where:

R = daily rental cost of desander or desilter

C = daily cost of chemical and bentonite

S = Solids removed, lb./day

Appendix C

DENSITY CONTROL

Density Increase Equations and Tables

Weight Up With Increasing Volume

To increase the density of a barrel of mud from W_1 to W_2

$$\text{Barite Required, lbs.} = \frac{1487.5(W_2 - W_1)}{35.42 - W_2}$$

Where:

W_1 = Initial weight, lb./gal

W_2 = Final weight, lb./gal

The barrels of W_2 mud per barrel of W_1 mud:

$$\text{BBLS of } W_2 \text{ mud} = 1 + \frac{W_2 - W_1}{35.42 - W_2}$$

Continued on next page

Density Increase Equations and Tables

Continued

Weight Up With Constant Volume

If you wish to increase the density of a mud without building new volume, a portion of the original mud must be discarded before addition of barite.

V_s = Volume of system we wish to maintain

V_d = Volume of mud to be discarded

$$V_d = V_s \left(\frac{W_2 - W_1}{35.42 - W_1} \right)$$

$$\text{Barite Required, lbs.} = V_s \left[\frac{1487.5(W_2 - W_1)}{35.42 - W_1} \right]$$

Continued on next page

TABLE C-1
BARITE REQUIRED TO INCREASE DENSITY 0.1 LB/GAL

Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl
9.0	5.66	.3	6.47	.7	7.60
.1	5.68	.4	6.50	.8	7.64
.2	5.70	.5	6.53	.9	7.68
.3	5.73	.6	6.56	16.0	7.72
.4	5.75	.7	6.59	.1	7.76
.5	5.77	.8	6.62	.2	7.80
.6	5.79	.9	6.65	.3	7.84
.7	5.82	13.0	6.68	.4	7.88
.8	5.84	.1	6.71	.5	7.92
.9	5.86	.2	6.74	.6	7.97
10.0	5.89	.3	6.77	.7	8.01
.1	5.91	.4	6.80	.8	8.05
.2	5.93	.5	6.83	.9	8.10
3	5.96	.6	6.86	17.0	8.14
.4	5.98	.7	6.89	.1	8.18

Continued on next page

TABLE C-1 - CONTINUED
BARITE REQUIRED TO INCREASE DENSITY 0.1 LB/GAL

Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl
.5	6.00	.8	6.93	.2	8.23
.6	6.03	.9	6.96	.3	8.28
.7	6.05	14.0	6.99	.4	8.32
.8	6.08	.1	7.02	.5	8.37
.9	6.10	.2	7.06	.6	8.42
11.0	6.13	.3	7.09	.7	8.46
.1	6.15	.4	7.13	.8	8.51
.2	6.18	.5	7.16	.9	8.56
.3	6.20	.6	7.19	18.0	8.61
.4	6.23	.7	7.23	.1	8.66
.5	6.26	.8	7.26	.2	8.71
.6	6.28	.9	7.30	.3	8.76
.7	6.31	15.0	7.34	.4	8.81
.8	6.34	.1	7.37	.5	8.87
.9	6.36	.2	7.41	.6	8.92

Continued on next page

TABLE C-1 - CONTINUED BARITE REQUIRED TO INCREASE DENSITY 0.1 LB/GAL					
Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl	Desired Mud Density, lb./gal	Barite, lb./bbl
12.0	6.39	.3	7.45	.7	8.97
.1	6.42	.4	7.48	.8	9.03
.2	6.45	.5	7.52	.9	9.08
		.6	7.56	19.0	9.14

Multiply the lb./bbl barite opposite desired mud weight by the number of points of mud weight increase to find the amount of barite necessary for that increase in weight.

Example: Increase mud density from 12.1 to 12.4 lb./gal. Read on chart 6.5 lb./bbl barite required to increase density 0.1 lb./gal to 12.4 lb./gal. Three point increase times 6.5 equal 19.5 lb./bbl barite required.

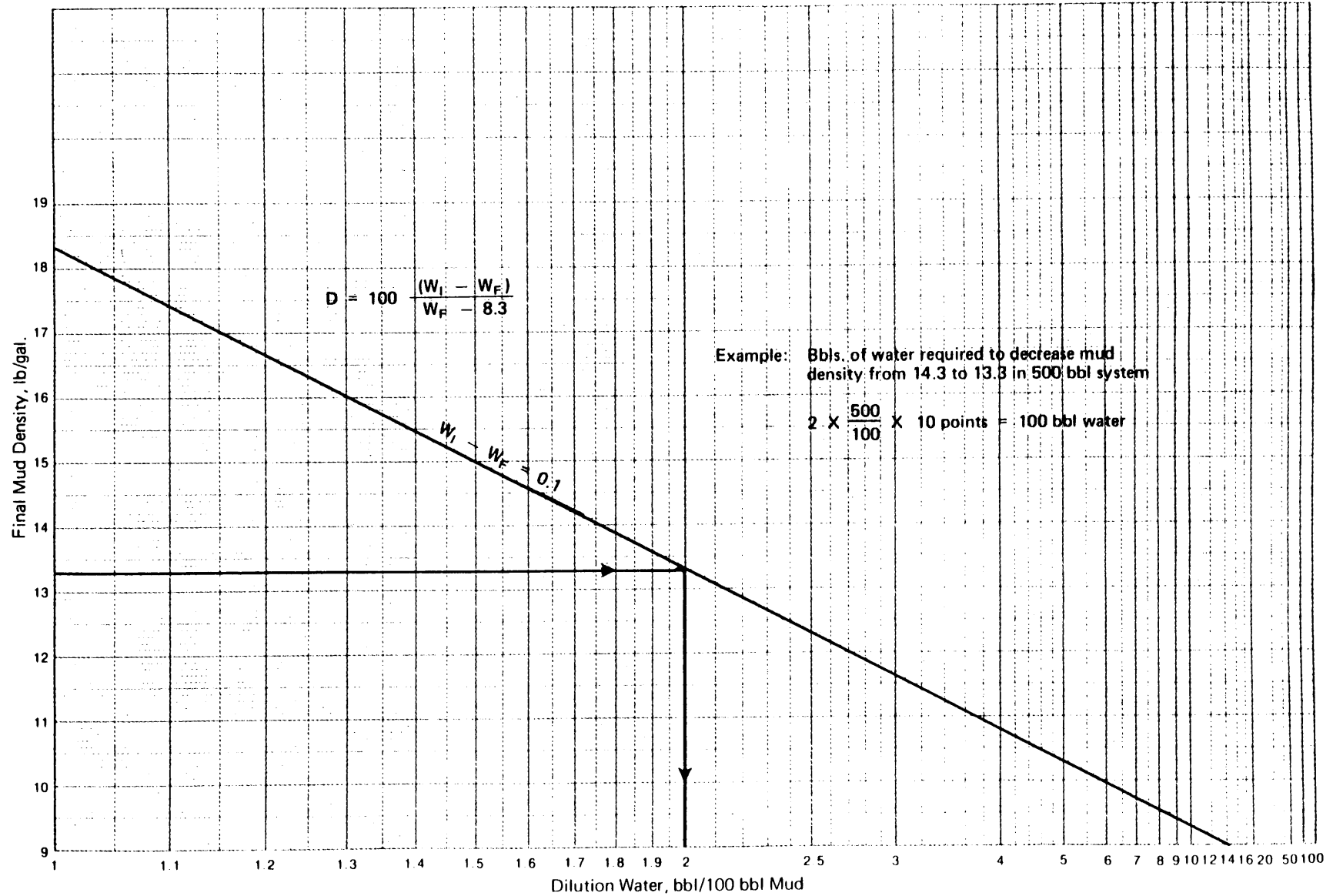
Volume increase = 6.75 bbl/100 sacks barite.

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TABLE C-2 BARITE REQUIREMENT FOR BBL, NEW MUD (Assumes Fresh Water and 2 Vol. % Bentonite)	
Mud Density, lb./gal	Barite, lb./bbl
11	135
12	190
13	245
14	300
15	355
16	410
17	465
18	520
19	575
Add 5.5 lb./bbl barite per 0.1 lb./gal increase in mud density.	

Example: 16.6 lb./gal = 410 + 6 X 5.5
 = 410 + 33
 = 443 lb./bbl Barite

Water required to decrease density 0.1 lb. / gal



Appendix D

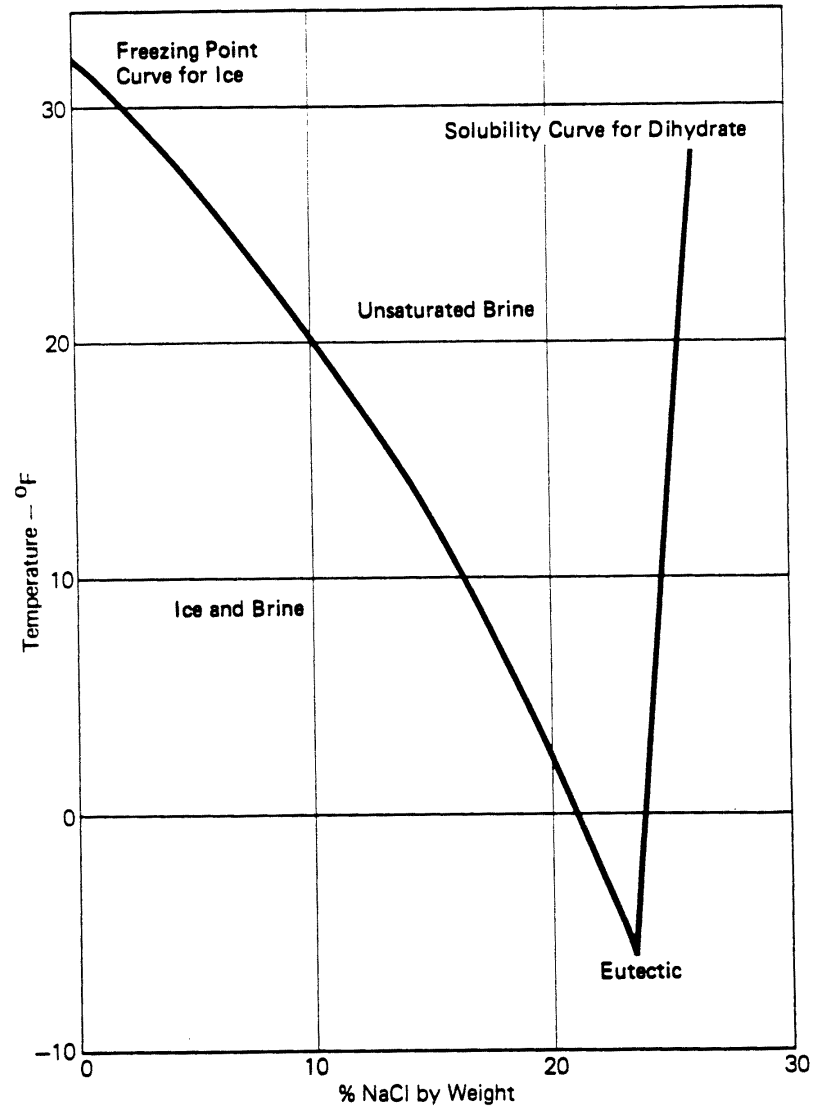
WATER MUD CHEMISTRY

EFFECT OF TEMPERATURE ON PROPERTIES OF WATER				
Temperature (°F)	Density		Viscosity C _p	Vapor Pressure PSIA
	(g/cc)	lb./gal		
50	0.9997	8.343	1.308	0.18
60	.9990	8.337	1.126	0.26
80	.9966	8.317	.861	0.51
100	.9931	8.288	.684	0.95
120	.9886	8.250	.560	1.69
140	.9832	8.205	.469	2.89
160	.9773	8.156	.400	4.74
180	.9704	8.098	.347	7.51
200	.9629	8.036	.304	11.53
220	.9553	7.972	.271	17.19
240	.9469	7.902	.242	24.97
260	.9378	7.826	.218	35.43
280	.9282	7.746	.199	49.20
300	.9183	7.664	.185	67.01
320	.9077	7.575	.174	89.66
340	.8962	7.479	.164	118.01
360	.8843	7.380	.155	153.04

SALT WATER DATA AT 68°F					
% NaCl by Wt	NaCl mg/l	Chloride mg/l	Solution Density lb./gal	NaCl Added lb./bbl of Water	Volume of Final Solution
0	0	0	8.33	00	1.0000
1	10,050	6,100	8.37	3.53	1.0036
2	20,250	12,290	8.43	7.14	1.0074
4	41,070	24,920	8.55	14.58	1.0152
6	62,480	37,910	8.67	22.34	1.0232
8	84,470	51,260	8.80	30.43	1.0317
10	107,100	64,990	8.92	38.89	1.0405
12	130,300	79,070	9.04	47.73	1.0497
14	154,100	92,900	9.17	56.18	1.0593
16	178,600	108,370	9.30	66.67	1.0694
18	203,700	123,000	9.43	78.83	1.0800
20	229,600	139,320	9.56	87.50	1.0912
22	256,100	155,400	9.70	98.72	1.1029
24	283,300	171,910	9.83	110.53	1.1152
26	311,300	188,890	9.97	122.97	1.1281

CALCIUM CHLORIDE DATA AT 60°F					
% CaCl₂ by Wt	Solution Density lb./gal	77-80% CaCl₂ lb./bbl of Water	Volume of Final Solution	94-97% CaCl₂ lb./bbl of Water	Volume of Final Solution
20	9.89	120.54	1.133	93.24	1.018
22	10.05	137.76	1.156	103.74	1.077
24	10.24	155.82	1.176	116.34	1.087
26	10.42	175.56	1.202	129.36	1.097
28	10.60	196.56	1.228	143.22	1.108
30	10.80	219.66	1.256	158.34	1.122
32	10.98	243.18	1.287	173.04	1.135
34	11.17	270.90	1.324	189.84	1.152
36	11.36	299.88	1.363	209.16	1.168
38	11.56	333.06	1.407	225.54	1.187
40	11.76	369.18	1.457	245.70	1.207

FREEZING POINTS OF SODIUM CHLORIDE SOLUTIONS



Water Mud Chemistry

Water chemistry is quite important to the performance of bentonite and other mud additives. A knowledge of the chemical composition of a mud is essential in diagnosing and treating mud problems.

Weights of Chemicals: (Atomic, Molecular, Equivalent)

The atomic weight of an element is the relative weight of an atom that element compared to carbon (12.000). An oxygen atom is one and a third times the weight of a carbon atom, thus has an atomic weight of 16.0.

Continued on next page

Atomic Weights of Common Elements in Mud Chemistry

Element	Symbol	Atomic Weight	Common Valence
Barium	Ba	137.4	+2
Calcium	Ca	40.1	+2
Carbon	C	12.0	+4
Chlorine	Cl	35.5	-1
Hydrogen	H	1.0	+1
Magnesium	Mg	24.3	+2
Oxygen	O	13.0	-2
Phosphorus	P	31.0	+5
Potassium	K	39.1	+1
Sulfur	S	32.1	-2
Sodium	Na	23.0	+1
Zinc	Zn	65.4	+2

Continued on next page

**Weights of
Chemicals:
(Atomic, Molecular,
Equivalent)
Continued**

Molecular weight is simply the sum of the atomic weights of elements which comprise a compound (molecule). For example, lime has three different elements, Ca, O, and H. There is one Ca, two O, and two H atoms which combine to form Ca(OH)₂. Its molecular weight is:

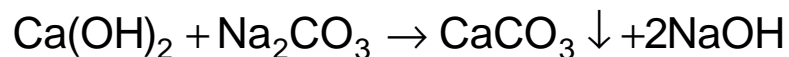
$$\text{Ca} = 1 \times 40.1 = 40.1$$

$$\text{O}_2 = 2 \times 16.0 = 32$$

$$\text{H}_2 = 2 \times 1.0 = \underline{2}$$

74.1 grams/mole

Most mud chemicals have molecules that are combinations of charged ions. When they are added to water, they ionize or break apart into the various ions that comprise the molecule. When lime is added to water, each molecule divides into one Ca⁺⁺ ion and two OH⁻ ions. If another soluble compound is added to the water, it produces ions which are free to react with those ions which are already in the water. For instance, if soda ash (Na₂CO₃) is added to water containing lime, the following reaction will occur:

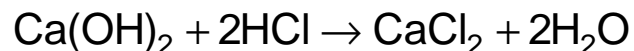


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**Weights of
Chemicals:
(Atomic, Molecular,
Equivalent)
Continued**

One molecule of lime will react with one molecule of soda ash to form one molecule of insoluble carbonate and two molecules of sodium hydroxide (caustic soda).

If hydrochloric acid (HCl) is added to water containing lime, the resulting reaction is:



One molecule of lime combines with 2 molecules of HCl to form one molecule of CaCl_2 and two molecules of water.

Note, that in these two reactions with lime, 1 to 1 mole ratios combined when soda ash was added and 1 to 2 mole ratios combined when hydrochloric acid was added. In order to eliminate the need for memorizing all of the combining mole ratios for all reactions, equivalent weights are used. One equivalent of compound or ion X will combine with one equivalent compound or ion Y.

Equivalent weight is the molecular (or ion weight) divided by the proper valence. The equivalent weight of lime is $74.1/2 = 37.05$. The equivalent weight of Ca^{++} is $40/2 = 20$. The equivalent weight of HCl is $36.5/1 = 36.5$. Therefore, 36.5 grams of HCl will combine with 37.05 grams of Ca(OH)_2 .

Milligrams per liter, mg/l and Milliequivalents per liter, meq/l

When determining the concentration of an ion in solution by titration, the concentration is often recorded in mg/l. For determining the correct treatment levels in muds and other chemical processes, mg/l is often converted to meq/l. mg/l divided by equivalent weight equals meq/l.

If meq/l of a contaminate is determined, it will take the same meq/l of treating agent to react with it. Meq/l of treating agent can be converted to lb./bbl as follows:

$\text{meq/l} \times \text{equivalent weight of treating agent} \times 0.00035 = \text{lb./bbl treating agent.}$

For example, Ca^{++} content of a mud is determined to be 1000 mg/l. This is equivalent to $1000/20 = 50$ meq/l.

Therefore, 50 meq/l of soda ash will be necessary to completely react with the Ca^{++} and precipitate it as CaCO_3 . The equivalent weight of soda ash is 53. The required lb./bbl of soda ash is:

$$50 \times 53 \times .00035 = 0.9275 \text{ lb./bbl of soda ash.}$$

pH and Alkalinity

In pure water, the hydrogen ion concentration (H^+) and the hydroxyl ion concentration (OH^-) are both equal to 10^{-7} moles/liter. The product of (H^+) X (OH^-) in water solutions is 10^{-14} moles/liter. The pH is defined as the negative logarithm of (H^+) and pOH is similarly the negative logarithm of (OH^-).

$$pH = \log 1/[H^+] \text{ and } pOH = \log 1/[OH^-]$$

$$[H^+] = 10^{-pH} \text{ and } [OH^-] = 10^{-pOH}$$

20°C, Relationship of (H^+), (OH^-), pH, and pOH				
	(H^+)	pH	(OH^-)	pOH
Acidic	10^{-0}	0	10^{-14}	14
	10^{-2}	2	10^{-12}	12
	10^{-4}	4	10^{-10}	10
	10^{-6}	6	10^{-8}	8
Neutral	10^{-7}	7	10^{-7}	7
Basic	10^{-8}	8	10^{-6}	6
	10^{-10}	10	10^{-4}	4
	10^{-12}	12	10^{-2}	2
	10^{-14}	14	10^{-0}	0

Continued on next page

pH and Alkalinity

Continued

Note that the hydroxyl ion concentration increases by a factor of 10 for each unit increase in pH.

One mole of NaOH per liter is equal to 14 lb./bbl of NaOH and has a solution of pH of 14. Consequently, 0.0014 lb./bbl of caustic soda is required to increase the pH of water from 7 to 10. This is equivalent to 0.1 meq/l of OH^- in solution at pH 10. This is obviously a very small concentration and would be quickly used up in a reaction. However, in mud filtrate there is often a reserve of hydroxyl ions which are produced by hydrolysis of other complex anions. This serves as a buffer and increases the acid neutralizing power of the filtrate. The half neutralization of CO_3^{2-} to HCO_3^- is one of the more common acid neutralizing reactions in mud filtrates. The reaction goes to completion at pH 8.3. One meq/l of acid is required to convert 2 meq/l of CO_3^{2-} to HCO_3^- .

Alkalinity tests are performed on mud filtrate to measure the acid neutralizing power of the filtrate and to indicate the amounts of OH^- , CO_3^{2-} , and HCO_3^- in the filtrate. P_f is the ml of 0.02N H_2SO_4 required to reduce the pH of one ml of filtrate to 8.3. The P_f is basically the amount of acid required to neutralize the OH^- and convert the CO_3^{2-} to HCO_3^- . The meq/l of acid required = $20 \times P_f$.

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pH and Alkalinity

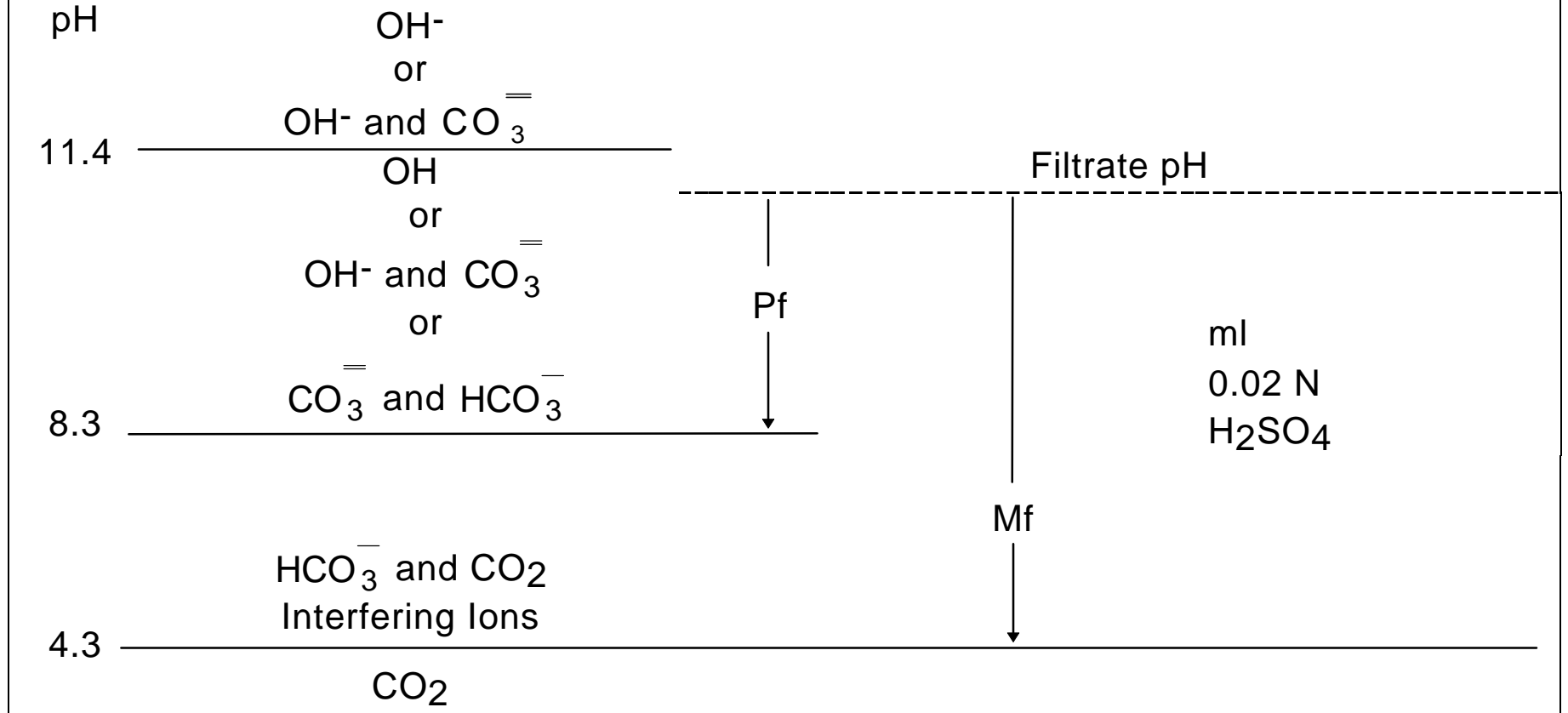
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Another alkalinity test which is normally performed on the filtrate is the M_f alkalinity. $M_f = P_f +$ ml of 0.02N H_2SO_4 required to reduce the pH from 8.3 to 4.3 is basically that required to convert HCO_3^- to CO_2 and water, and to react with any organic acids or buffering ions.

The common alkalinity producing ions which can be present at various pH levels are shown in the following diagram in relation to the P_f and M_f alkalinities.

Continued on next page

Ions Which Can Be Present At Various pH Levels



Continued on next page

pH and Alkalinity

Continued

If there were no interfering ions present, the P_f and M_f alkalinities could be used to calculate the amounts of OH^- , CO_3 , and HCO_3 present in the filtrate. However, the presence of organic acids or buffering ions cause the M_f determination to indicate more CO_3 and HCO_3 than are actually present. This is the usual case in mud filtrate and the M_f determination is only a very rough indicator of the amount of CO_3 and HCO_3 present. As a general guide, M_f values above 5 ml indicate that excessive amounts of CO_3 and HCO_3 are probably present in the mud.

When excessive concentrations of CO_3 and HCO_3 are suspected, another titration procedure can be used to determine their concentrations, which does not rely on the M_f determination. A description of this procedure is shown in API RP 13B, Standard Procedure for Testing Drilling Fluids.

In the P_1 determination, caustic solution is added to convert any HCO_3 in the filtrate to CO_3 . All HCO_3 is converted to CO_3 at pH 11.4. Next, $BaCl_2$ is added to precipitate all of the CO_3 as barium carbonate. This leaves only the OH^- which was originally in the filtrate, if any, plus the OH^- which was added less that consumed in the HCO_3 to CO_3 conversion.

Continued on next page

pH and Alkalinity

Continued

In the P_2 determination, the total OH^- which was added in the P_1 determination is measured. If P_2 is less than P_1 , it indicates that none of the added OH^- was consumed in conversion of HCO_3^- to CO_3^{2-} . Thus only OH^- and CO_3^{2-} exist in the filtrate. The difference in P_1 and P_2 is the amount of acid required to neutralize the OH^- in the sample. Consequently, $\text{meq/l (OH)} = 20 (P_1 - P_2)$. The amount of acid required to neutralize the OH^- subtracted from the original P_f should indicate the amount of acid required to convert the CO_3^{2-} to HCO_3^- in the original P_f determination. Therefore, $\text{meq/l (CO}_3^{2-}) = 40 \{P_f - (P_1 - P_2)\}$.

If P_2 is greater than P_1 it indicates that some of the OH^- added in the P_1 determination was consumed in converting HCO_3^- to CO_3^{2-} . The difference in P_2 and P_1 represents the amount of added OH^- used in converting HCO_3^- to CO_3^{2-} . Thus, $\text{meq/l (HCO}_3^-) = 20(P_2 - P_1)$. If HCO_3^- is present in the filtrate, then no OH^- can be present.

Therefore, all of the acid used in the original P_f titration was used in converting CO_3^{2-} to HCO_3^- , and $\text{meq/l (CO}_3^{2-}) = 40 P_f$.

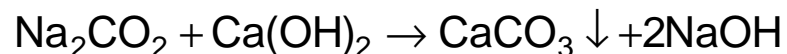
Knowing the concentrations of CO_3^{2-} and HCO_3^- in the mud, the amount of a soluble calcium compound necessary to precipitate

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pH and Alkalinity

Continued

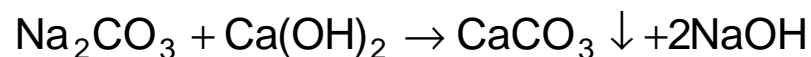
them as insoluble calcium carbonate can be calculated. If lime is used as the calcium source than 0.0129 lb./bbl of lime is required to precipitate one meq/l of CO₃.



Note, that for each pound of lime which is added, 1.08 pounds of NaOH will be produced in the reaction. This may lead to excessive pH when large amounts of CO₃ are being precipitated with lime. Addition of acidic materials such as lignosulfonate and lignite after treatment with lime will help to reduce the pH and also to replenish the system with these materials which may have been physically extracted by the precipitate. To precipitate HCO₃, it first must be converted to CO₃ since Ca(HCO₃)₂ is soluble. Addition of one meq/l of lime per meq/l of HCO₃ will convert all of the HCO₃ to CO₃. Half of the CO₃ is precipitated as CaCO₃ and the other half remains in solution as Na₂CO₃.



To precipitate the remaining CO₃, an addition meq/l of lime is required.



Continued on next page

pH and Alkalinity

Continued

In other words, to completely convert all of the HCO_3 to CO_3 and precipitate it as CaCO_3 , 2 meq/l of lime per meq/l of HCO_3 is required. This amounts to 0.0258 lb./bbl of lime per meq/l of HCO_3 . For each pound of lime which is added, 0.54 pounds of NaOH will be produced by the reaction.

Calcium, Lime, and Cement Contamination

When calcium, lime or cement exist in the mud in excessive concentrations, the treating procedures are the exact opposite of those used in control CO_3 and HCO_3 . Soda ash is added to precipitate calcium and sodium bicarbonate is added to precipitate lime or cement.

The calcium and magnesium concentration (total hardness) in a mud filtrate is normally measured in a mud check and is reported as Ca^{++} in ppm. If magnesium actually exists in the filtrate, this procedure can lead to confusion in treating the mud to precipitate the Ca^{++} . Calcium is precipitated by CO_3 but Mg^{++} is not effectively precipitated, since MgCO_3 is much more soluble than CaCO_3 . Another titration which is specific for Ca^{++} should be run. The Mg^{++} concentration can then be calculated by difference between the two titrations.

$$\text{Total Harness (Ca}^{++} \text{ mg/l)} = \frac{\text{ml of Standard Versenate} \times 400}{\text{ml of filtrate}}$$

Continued on next page

**Calcium, Lime, and
Cement
Contamination**
Continued

Manver Indicator and Strong Buffer solution are used in this titration. The titration which is specific to calcium is also a versenate titration except calgon indicator is used and 8 N NaOH or KOH is used in place of the strong buffer.

$$\text{Calcium, mg/l} = \frac{\text{ml of Standard Versenate} \times 400}{\text{ml of filtrate}}$$

The magnesium concentration can be calculated from these two measurements.]

$$\text{Magnesium, mg/l} = (\text{Total hardness} - \text{calcium, ppm})0.606$$

In order to calculate the amount of soda ash required to precipitate the indicated amount of calcium in a mud, the Ca++ concentration in mg/l should be converted to meq/l.

$$\text{Ca}^{++}, \text{ meq/l} = \frac{\text{Ca}^{++} \text{ mg/l}}{20}$$

The same meq/l of soda ash will be required to precipitate the calcium. One meq/l of soda ash is equal to 0.01855 lb./bbl.

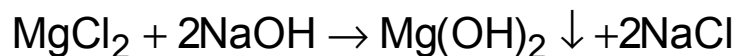
You should not precipitate all of the calcium out of the mud. About 100 mg/l should be left in the mud as a precaution against overtreatment with soda ash and development of a CO₃ problem.

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**Calcium, Lime, and
Cement
Contamination**
Continued

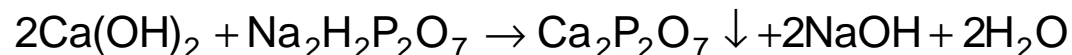
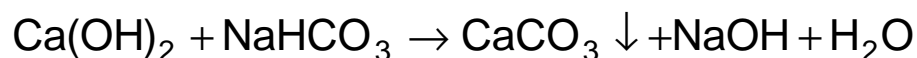
This amounts to using about 0.1 lb./bbl less soda ash than is calculated for complete removal of the calcium.

Additions of NaOH are used to precipitate magnesium as insoluble Mg(OH)₂.



$$\text{Mg}^{++}, \text{meq/l} = \frac{\text{Mg} + \text{mg/l}}{12.1}$$

One meq/l of NaOH (0.014 lb./bbl) will precipitate one meq/l of Mg⁺⁺. When an excessive amount of lime or cement is present in a mud, the high alkalinity as well as the calcium ion concentration must be controlled. This necessitates the use of a material that will neutralize OH⁻ as well as precipitate Ca⁺⁺. Sodium bicarbonate and sodium acid pyrophosphate (SAPP) are the two most commonly used treating agents. These reactions are as follows:



In both of these reactions, one meq/l of treating agent will precipitate all of the Ca⁺⁺ in two meq/l of lime and will neutralize half of the OH⁻. To react with one meq/l of lime, 0.0147 lb./bbl of sodium bicarbonate or 0.0194 lb./bbl of SAPP is required. Overtreatment with either of these materials should be avoided.

Continued on next page

**Calcium, Lime, and
Cement
Contamination**
Continued

An estimate of the lime or reactive cement content of a mud can be made from an alkalinity measurement (P_m) on the mud. This measurement is made in the same manner as the P_f determination except whole mud is used instead of filtrate. The ml of 0.02 N H_2SO_4 required to reduce the pH of a one ml sample of mud to 8.3 is the P_m alkalinity of a mud. P_m is the acid neutralizing power of the undissolved solids in a mud and the filtrate. $P_m \times 20 = \text{meq/l}$ of acid neutralized by the mud. If all of the alkalinity is assumed to be due to lime or cement, then the meq/l of lime would be $P_m \times 20$ and would require half this amount of sodium bicarbonate or SAPP to completely react with both the dissolved and undissolved lime in the mud.

When treating cement contamination, it is wise to suspend treatment when the P_m has been reduced to three times the P_f . This prevents overtreatment with $NaHCO_3$ or SAPP which can cause a more serious mud problem than the cement.

Contaminants and Treating Agents

The following is a list of common contaminants and their treating agents.

Contaminants	Treating Agent	Meq/l of Treating Agent
		Per meq/l of Contaminant
Calcium	Soda ash	1
Lime	Sodium Bicarbonate	0.5
Carbonate	Lime, gyp, or CaCl_2	1
Bicarbonate	Lime	2
Magnesium	Caustic	1
Sulfide	Zinc basic carbonate	1
Sulfate	Barium carbonate	1

The attached table gives required data for calculating treatment levels of the common water chemistry treating agents.

Continued on next page

EQUIVALENT WEIGHTS				
ION	Symbol	Ionic Weight	Equivalent Weight	mg/l per meq/l
Hydrogen	H ⁺¹	1	1	1
Potassium	K ⁺¹	39.1	39.1	39.1
Sodium	Na ⁺¹	23	23	23
Barium	Ba ⁺²	137.4	68.7	68.7
Calcium	Ca ⁺²	40.1	20	20
Magnesium	Mg ⁺²	24.3	12.1	12.1
Zinc	Zn ⁺²	65.4	32.7	32.7
Hydroxide	OH ⁻¹	17	17	17
Chloride	Cl ⁻¹	35.5	35.5	35.5
Nitrate	NO ₃ ⁻¹	62	62	62
Bicarbonate	HCO ₃ ⁻¹	61	61	61
Carbonate	CO ₃ ⁻²	30	30	30
Sulfate	SO ₄ ⁻²	48	48	48
Sulfide	S ⁻²	16	16	16

EQUIVALENT WEIGHTS				
Common Name	Chemical Formula	Molecular Weight	Equivalent Weight	meq/l Per lb./bbl
Caustic Soda	NaOH	40	40	71.43
Lime	Ca(OH) ₂	74	37	77.22
Gypsum	CaSO ₄ • 2H ₂ O	172	86	33.22
Calcium Chloride	CaCl ₂	111	55.5	51.48
Soda Ash	Na ₂ CO ₃	106	53	53.91
Sodium Bicarbonate	NaHCO ₃	84	84	34.01
Barium Carbonate	BaCO ₃	197.4	98.7	28.95
Zinc Basic Carbonate	Zn(OH) ₂ • ZnCO ₃	224.8	56.2	50.84
Zinc Chloride	ZnCl ₂ • 2H ₂ O	172.4	86.2	33.15
Hydrogen Sulfide	H ₂ S	34.1	17	167.57
Sodium Sulfide	Na ₂ S	78.1	39	73.17

Chemical Analysis for Soluble Sulfides in Water-Base Fluids

Equipment

9.59 The following materials are required to perform the analysis of total soluble sulfides using a solids-free filtrate sample.

NOTE: *Total soluble sulfides include the sulfide ($S^{=}$) and bisulfide (HS^{-}) ions.*

- a. The Garret Gas Train (GGT) apparatus, as shown in Fig. 9.2, consists of: a transparent plastic gas train, an inert gas supply and pressure regulator, a floating-ball flowmeter and a Dräger tube.
 - b. Dräger H_2S -Analysis Tubes:
 1. low range - marked H_2S 100/a - (No. Ch-291-01) and
 2. high range - marked H_2S 0.2%/A - (No. CH-281-01).
 - c. Lead-acetate paper disks (see note Par. 9.76).
 - d. Sulfuric acid: Approximately 5N, reagent grade.
 - e. Octanol defoamer in a dropper bottle.
 - f. Hypodermic syringes: one 10-cm³ with 1.5 inch (38 mm) 21 gauge needle (for acid), and one each 10-cm³, 5-cm³ with 1.5 inch (38 mm) 21 gauge needle (for sample).
 - g. Nitrogen (N_2) bottle with a low-pressure regulator (preferred) or CO_2 gas cartridges.
-

Description

9.60 The Garret Gas Train separates the gas from the liquid, thereby preventing contamination of the H₂S-detector by the liquid phase. A Dräger tube is the preferred H₂S detector for quantitative sulfide analysis, although a lead-acetate paper disk can be accommodated in the Garrett Gas Train for positive or negative determination of the presence of H₂S. If a positive indication of sulfide is noted by discoloration of the lead-acetate paper, a Dräger tube should be used for quantitative analysis. A Dräger tube responds to H₂S by progressively darkening along its length as the H₂S reacts with the reagent. Two types of Dräger tubes will span a sufficiently wide range for sulfide analysis of muds and filtrates. The low-range Dräger tube, H₂S 100/a, is white until H₂S turns it brownish-black. The high-range Dräger tube, H₂S 0.2%/A, is pale blue until H₂S turns it jet black. No known common mud component or contamination causes this coloration of the Dräger tubes as does H₂S.

Procedure

9.61 Be sure the gas train is clean, dry and on a level surface, with the top removed.

NOTE: Moisture in the train can cause the ball in the flowmeter to flat erratically and may affect the accuracy of the Dräger tube reading.

Continued on next page

Procedure
Continued

9.62 Add 20 cm³ deionized water to Chamber 1.

9.63 Add 5 drops octanol defoamer to Chamber 1.

9.64 See table 9.2 for sample volume and type of Dräger tube required for the expected sulfide range. Select the proper type Dräger tube. Break the tip from each end of the tube.

TABLE 9.2 DRÄGER TUBE IDENTIFICATION, SAMPLE VOLUMES AND TUBE FACTORS TO BE USED FOR VARIOUS SULFIDE RANGES			
1	2	3	4
Sulfide Range (mg/l)	Sample Volume (cm ³)	Dräger Tube Identification (See tube body)	Tube Factor (See Pr. 9.76)
1.5 to 30	10.0	H ₂ S 100/a	12
3 to 60	5.0	H ₂ S 100/a	12
6 to 120	2.5	H ₂ S 100/a	12
60 to 1020	10.0	H ₂ S 0.2%/A	600*
120 to 2040	5.0	H ₂ S 0.2%/A	600*
240 to 4080	2.5	H ₂ S 0.2%/A	600*

Continued on next page

Procedure

Continued

**The Tube Factor 600 is based on a Batch Factor (stenciled on box) of 0.40. For another Batch Factor (as stenciled on box), a corrected Tube Factor should be calculated:*

$$\text{Corrected Tube Factor} = 600 \left(\frac{\text{Batch Factor}}{0.40} \right)$$

9.65 Install the Dräger tube with the arrow pointing downward into the bored receptacle. Likewise, install the flowmeter tube with the word *Top* upward. Be sure O-rings seal around the body of each tube.

9.66 Install the top of the gas train and hand tighten all screws evenly to seal the O-rings.

9.67 With the regulator backed off, connect the nitrogen bottle to the dispersion tube of Chamber 1 using flexible tubing. If a CO₂ cartridge is used, install and puncture cartridge and connect to dispersion tube as shown in **Fig. 9.2**.

9.68 Attach the flexible tubing from Chamber 3 outlet to the Dräger tube, as shown in **Fig. 9.2**.

NOTE: *Use only latex rubber or inert plastic tubing. Do not clamp flexible tubing; unclamped tubing provides pressure relief in event of over-pressurization.*

9.69 Adjust the dispersion tube in Chamber 1 to approximately 0.5 cm above the bottom.

Continued on next page

Procedure
Continued

9.70 Gently flow N₂ or CO₂ for a 30-second period to purge air from the system. Check for leaks. Shut off the carrier gas.

9.71 Using the API room-temperature filtration procedure, collect a sufficient volume of solids-free filtrate for analysis. (If a low concentration of soluble sulfides is to be detected, a large volume of a filtrate is required. Use **Table 9.2** as a guide.)

NOTE: Care should be taken during mud sampling, filtration and analysis to avoid extended exposure of sample to the air because sulfides are rapidly lost by air oxidation.

9.72 Inject a measured volume of the filtrate sample into Chamber 1 through the rubber septum, using a hypodermic syringe and needle.

9.73 Slowly inject 10 cm³ sulfuric acid solution into Chamber 1 through rubber septum, using a hypodermic syringe and needle.

9.74 Immediately restart the carrier gas flow. The flow rate should be maintained between 200-400 cm³ per minute.

NOTE: One CO₂ cartridge should provide about 15-20 minutes of flow at this rate.

9.75 Observe changes in appearance of the Dräger tube. Note and record the maximum darkened length (in units marked on the tube) before the front starts to smear. Continue flowing for a total of 15

Continued on next page

Procedure

Continued

minutes, although the front may attain a diffuse and feathery coloration. In the high-range tube an orange color (caused by SO₂) may appear ahead of the black front if sulfites are present in the sample. The orange SO₂ region should be ignored when recording darkened length,

9.76 Using the measured Sample Volume, the Dräger tube's maximum Darkened Length and the Tube Factor from Table 9.2, calculate sulfides in the sample:

$$\text{GGT Sulfides, mg/l} = \frac{(\text{Darkened Length*})(\text{Tube Factor})}{(\text{Sample Volume, cm}^3)}$$

**In units marked on the tube.*

NOTE: A lead-acetate paper disk fitted under the O-rings of Chamber 3 can be substituted for the Dräger tube in the Garrett Gas Train. The lead-acetate paper will show qualitatively the presence or absence of sulfides in the sample. A dark discoloration of the paper is a positive indication of sulfides. After the positive indication, the Dräger tube should be used for quantitative analysis.

9.77 To clean the gas train remove the flexible tubing and remove the top. Take the Dräger tube and flowmeter out of the receptacles and plug the holes with stoppers to keep them dry. Wash out the

Continued on next page

Procedure

Continued

chambers with warm water and mild detergent, using a soft brush. Use a pipe cleaner to clean the passages between chambers. Wash, rinse and then blow out the dispersion tube with a dry gas. Rinse the unit with deionized water and allow to drain dry.

9.78 Specifications for the Garrett Gas Train materials and nominal dimensions are:

a. Body

Chamber 1:

Depth	3.54 in (90 mm)
Diameter	1.52 in. (38 mm)

Chamber 2:

Depth	3.54 in (90 mm)
Diameter	1.18 in. (30 mm)

Passages between Chambers:

Diameter	0.08 in (2.0 mm)
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Material:

Lucite® or equivalent transparent material or glass which is inert to acid, sulfides and hydrogen sulfide gas.

Continued on next page

Procedure

Continued

b. Dispersion Tube

Stem:

Diameter 0.315 in. (8.0 mm)

Length approx. 5.9 in (150 mm)

Dispersion Frit (Bell-shaped ASTM 4-5.5 Fine):

Diameter 1.18 in. (30 mm)

Material:

Pyrex® or equivalent glass

c. Carrier Gas

Type inert to hydrogen sulfide, acid, Dräger tube's reagents. Carbon dioxide, is acceptable but nitrogen is preferred. (Avoid air or other oxygen-containing gases.)

d. Flow Meter

Floating ball type preferred, capable of measuring 300 cm³ per minute of CO₂ gas.

e. Flexible Tubing

Type inert to hydrogen sulfide and carrier gas. Latex, rubber or Tygon® plastic is preferred.

f. Fittings and Rigid Tubing

Type inert to hydrogen sulfide and acid.

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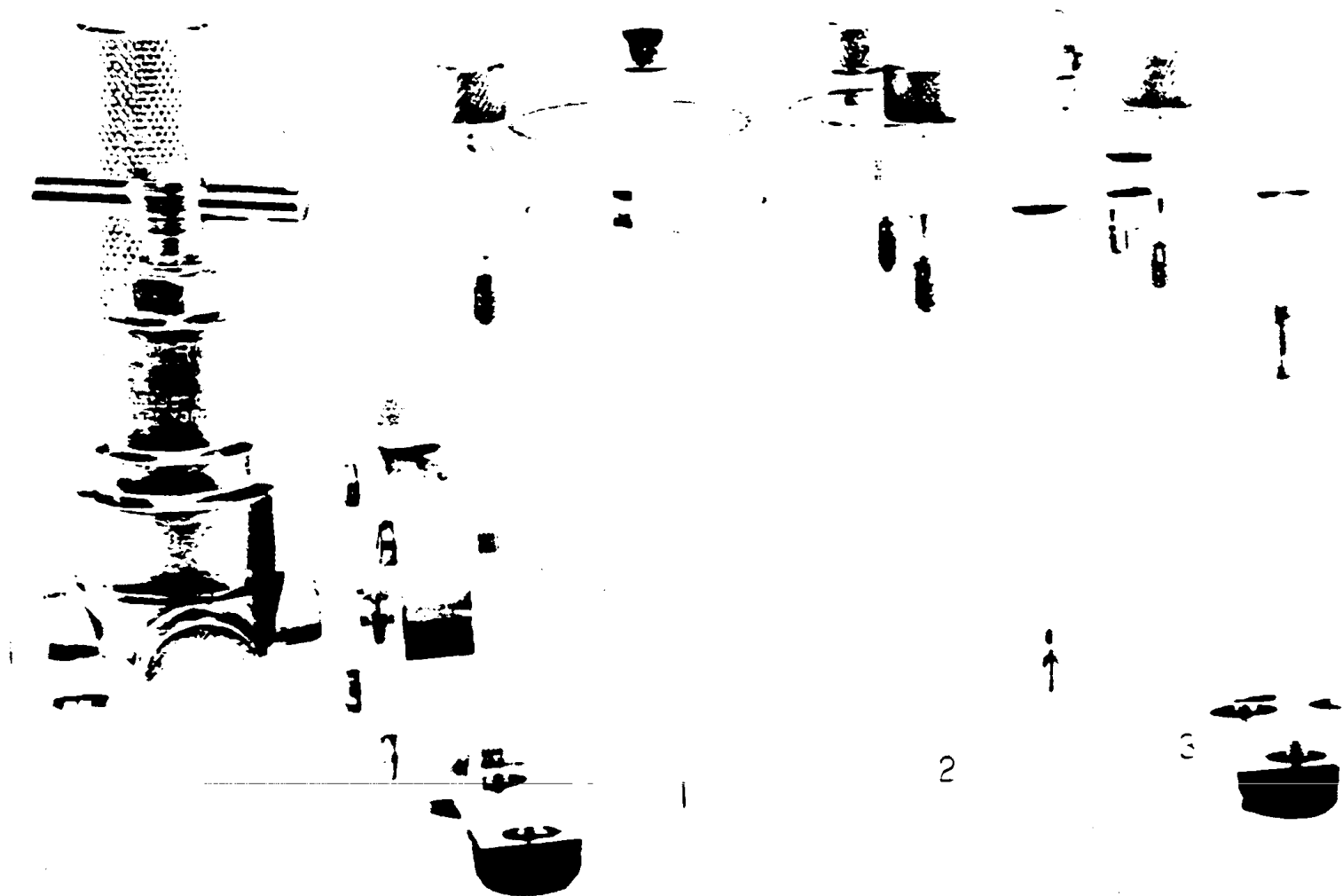


Fig. 9.2
Garrett Gas Train For Analysis of Soluble Sulfides

Chemical Analysis For Soluble Carbonates in Water-Base Fluids

Equipment

A.1 The following materials are required to perform the analysis of total soluble carbonates using a solids-free filtrate sample.

NOTE: Total soluble carbonates include the carbonate (CO_3) and bicarbonate (HCO_3) ions.

- a. The Garrett Gas Train (GGT) apparatus consists of : a transparent plastic gas train, an inert gas supply (N_2 or N_2O) with pressure regulator, a CO_2 Dräger tube, Dräger gas bag and a Dräger hand pump.
- b. Dräger CO_2 analysis tub - marked CO_2 0.01%/a - (No. CH-308-01)
- c. Dräger one liter Alcotest gas bag - (No. 7626425).
- d. Dräger Multigas Detector hand-operated vacuum pump, Model 31.
- e. Stopcock (2-way bore), 8 mm glass.
- f. Sulfuric acid: approximately 5N, reagent grade.
- g. Octanol defoamer in a dropper bottle.
- h. Hypodermic syringes: one 10- cm^3 (for acid) and one each 10- cm^3 , 2.5- cm^3 and 1.0- cm^3 (for sample)

Continued on next page

Equipment
Continued

- i. Hypodermic needles: two 1.5 inch (38 mm) 21-gauge needles.
- j. Nitrogen (N₂) bottle with low-pressure regulator (preferred), or N₂O gas cartridges (e.g. Whippets #561241 by Walter Kidde and Co. Inc., Belleville, NJ)

NOTE: *Nitrogen is preferred over N₂O as the carrier gas. Because N₂O cools upon expansion and chills the diaphragm in the regulator, prolonged N₂O flow will cause the regulator to perform erratically.*

Description

A.2 The Garret Gas Train separates gas from the liquid, thereby preventing contamination of the CO₂-detecting Dräger tube by the liquid phase. The CO₂ Dräger tube responds to the CO₂ passing through it by progressively staining (purple) along its length as the CO₂ reacts with a hydrazine chemical which causes a crystal violet indicator to turn purple. The stain length is sensitive to the amount of CO₂ present, but it also responds to the CO₂ distribution, total volume and flow rate of gas passed through the tube. Therefore, for reliable results the gas from the train is first captured in a one-liter gas bag (to allow CO₂ to mix uniformly) and second, the contents of the bag is drawn through the Dräger tube using ten strokes of the Dräger hand pump. Ten strokes draws exactly one liter of gas through the tube, which empties the bag.

Procedure

A.3 Be sure the gas train is clean, dry and on a level surface, with the top removed.

NOTE: If CO₂ has been used as the carrier gas in the previous test (i.e., sulfide analysis) the regulator, tubing, and dispersion tube should be purged with N₂ or N₂O gas at this time.

A.4 Add 20 cm³ deionized water to Chamber 1.

A.5 Add 5 drops octanol defoamer to Chamber 1.

A.6 Install the top on the gas train and hand-tighten evenly to seal all O-rings.

A.7 Adjust the dispersion tube to 0.5 cm of f bottom.

A.8 With regulator backed off, connect carrier gas supply to glass dispersion tube of Chamber 1 using flexible tube.

A.9 Flow carrier gas through train for 1 minute to purge air from the system. Check for leaks in gas train unit.

A.10 Fully collapse the gas bag and simultaneously check the system for leaks. To do this, connect gas bag and stopcock to hand pump, as shown in **Figure A.2**. (use a discarded Dräger tube as connection and start with the bag essentially empty.) Fully depress and release the hand pump. When the bag is completely empty and free of leaks, the pump will remain depressed for several minutes. If

Continued on next page

Procedure
Continued

leakage is detected check the pump and all connections. To check the pump alone, insert a sealed Dräger tube into the pump opening and depress bellows. It will remain depressed if pump does not leak.

A.11 With bag fully collapsed, install flexible tubing from the stopcock and bag into the outlet of Chamber 3, as seen in Figure A.1.

A.12 Inject a measured volume of solids-free filtrate into Chamber 1 through septum with a hypodermic syringe and needle. **See Table A-1.**

TABLE A-1			
DRÄGER TUBE IDENTIFICATION, SAMPLE VOLUMES AND TUBE FACTOR TO BE USED FOR VARIOUS CARBONATE RANGES			
1	2	3	4
Carbonate Range (mg/l)	Sample Volume (cm ³)	Dräger Tube Identification (see tube body)	Tube Factor (see A.19)
25 to 750	10.0	CO ₂ 0.01%/a	25,000
50 to 1500	5.0	CO ₂ 0.01%/a	25,000
250 to 7500	1.0	CO ₂ 0.01%/a	25,000

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Procedure

Continued

A.13 Slowly inject 10 cm³ sulfuric acid solution into Chamber 1 through rubber septum using a clean syringe and needle. Gently shake the gas train to mix acid with sample in Chamber 1.

A. 14 Open the stopcock on the gas bag. Restart gas flow and allow gas bag to fill steadily during a 10-minute interval. When the bag is firm to the touch (do not burst it) shut of flow and close the stopcock. Immediately proceed to next step.

A.15 Break the tip off each end of the Dräger tube.

A.16 Remove the tubing from Chamber 3 outlet and reinstall it onto the upstream end of the Dräger tube. (Observe that an arrow on the tube indicates gas flow direction.) Attach Dräger hand pump to downstream end of Dräger tube, as shown in **Fig. A.2**.

A.17 Open the stopcock on the bag. With steady hand-pressure fully depress the hand pump. Release pump so that gas flows out of the bag and through the Dräger tube. Operate the pump and count the strokes until the bag is empty. (Ten strokes should empty the bag. More than ten strokes indicates leakage has occurred and test results will not be correct.

A.18 Observe a purple stain on the Dräger tube if CO₂ was present in the gas bag and record the stain length in units marked on the Dräger tube. (Include the faint blue tinge in the purple stain-length reading.)

Continued on next page

Procedure
Continued

A.19 Using the measured Sample Volume, the Dräger tube's Stain Length and Tube Factor of 25,000 (**See Table A.1**), calculate total soluble carbonates ($\text{CO}_3 + \text{HCO}_3$) in the filtrate sample using equation below.

$$\text{GGT Carbonates, mg/l} = \frac{(\text{Stain Length}) \times (25,000)}{(\text{Sample Volume, cm}^3)}$$

A.20 To clean the gas train remove the flexible tubing and remove the top. Wash out the chambers with warm water and mild detergent, using a brush. Use a pipe cleaner to clean the passages between chambers. Wash, rinse and then blow out the dispersion tube with gas. Rinse the unit with deionized water and allow to drain dry. Be sure to periodically replace the disposable gas bag to avoid leaks and contamination in the bag. (Bag replacement is suggested after 10 analyses.)

A.21 Specifications for the Garrett Gas Train materials and nominal dimensions are:

a. Body

Chamber 1:

Depth	3.54 in. (90 mm)
Diameter	1.52 in. (38 mm)

Continued on next page

Procedure
Continued

Chamber 2 and 3:

Depth 3.54 in. (90 mm)

Diameter 1.18 in. (30 mm)

Passages between Chambers:

Diameter 0.08 in. (2.0 mm)

Material:

Lucite® or equivalent transparent material or glass which is inert to acid, carbonates and carbon dioxide gas.

b. Dispersion Tube

Stem:

Diameter 0.315 in. (8.0 mm)

Length approx. 5.9 in. (150 mm)

Dispersion Frit (Bell-shaped ASTM 4-5.5 Fine):

Diameter 1.18 in. (30 mm)

Material:

Pyrex® or equivalent glass

Continued on next page

Procedure

Continued

c. Carrier Gas

Type inert to carbon dioxide, acid, and Dräger tube's reagents. Nitrogen is preferred, or N₂O gas.

d. Flexible Tubing

Type inert to carbon dioxide and carrier gas. Latex rubber or Tygon® plastic is preferred.

e. Fittings and Rigid Tubing

Type inert to carbon dioxide and acid.

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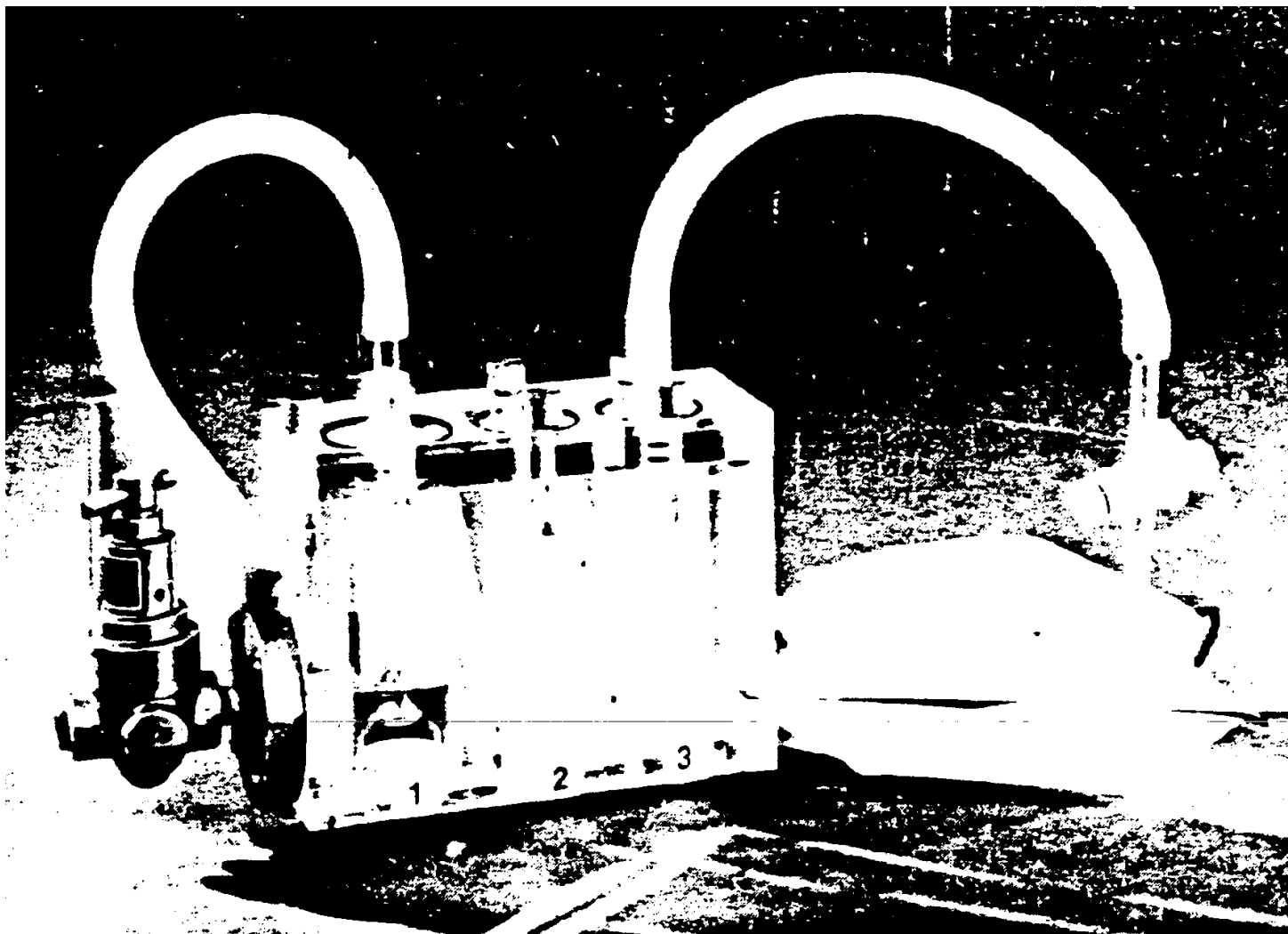
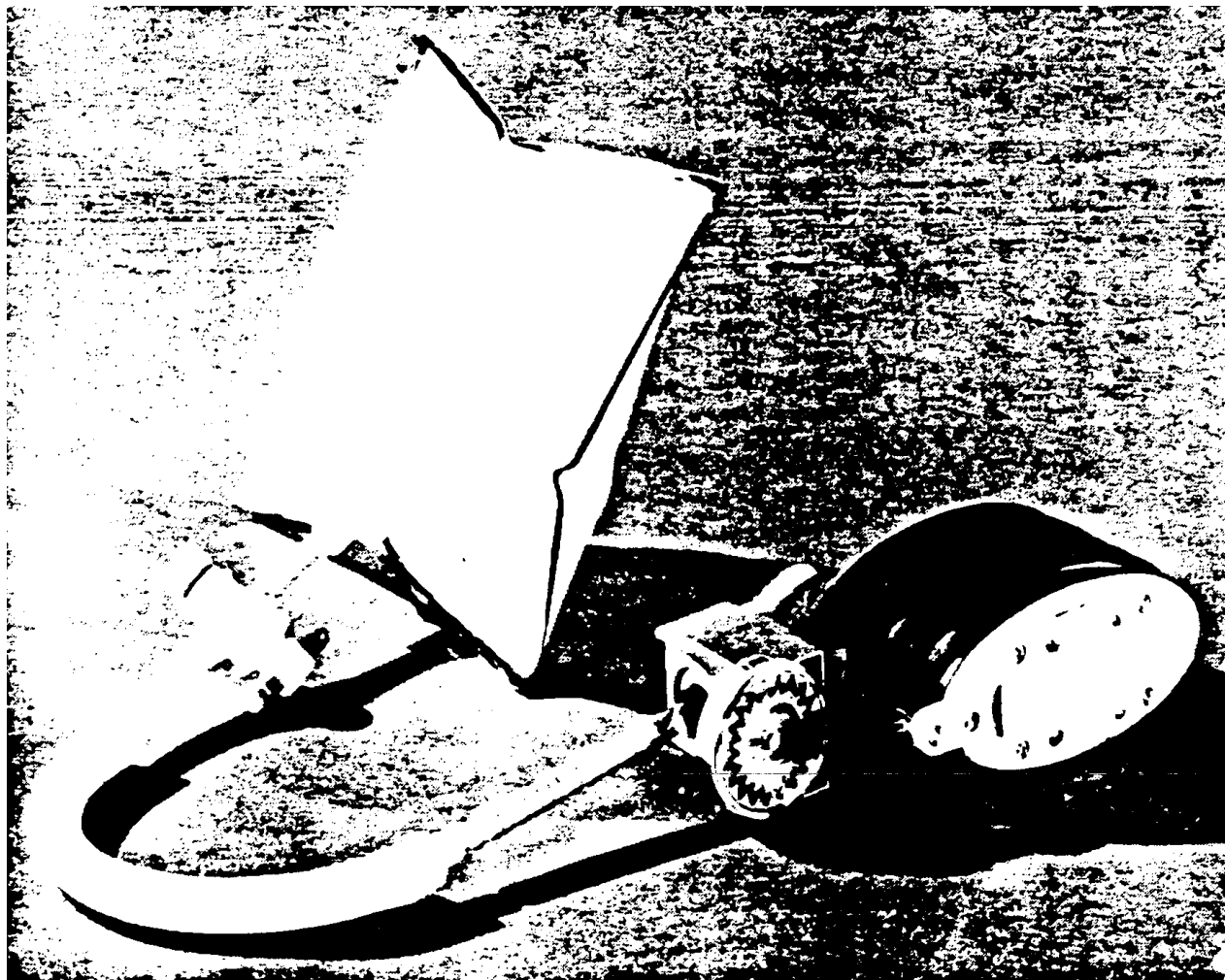


Fig. A.1
Step 1 - Freeing Carbonates as CO₂ Gas

Fig A.2
Step 2 - Analyzing CO₂ with Dräger Tube



Garrett Gas Train for Analysis of Soluble Carbonates

Appendix E

VOLUME AND DISPLACEMENT TABLES

CAPACITY OF HOLE					
Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel	Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel
4	.0155	64.52	13	.1642	6.09
$\frac{1}{4}$	.0175	57.14	$\frac{1}{4}$	.1705	5.87
$\frac{1}{2}$	.0197	50.76	$\frac{1}{2}$	.1770	5.65
$\frac{3}{4}$	.0219	45.66	$\frac{3}{4}$	.1836	5.45
5	.0243	42.15	14	.1904	5.25
$\frac{1}{4}$	.0268	37.31	$\frac{1}{4}$	.1972	5.07
$\frac{1}{2}$	.0294	34.01	$\frac{1}{2}$	.2042	4.90
$\frac{3}{4}$	.0321	31.15	$\frac{3}{4}$	.2113	4.73
6	.0349	28.65	15	.2186	4.57
$\frac{1}{4}$	.0379	26.39	$\frac{1}{4}$	.2259	4.43
$\frac{1}{2}$	.0410	24.39	$\frac{1}{2}$	.2334	4.28
$\frac{3}{4}$	.0443	22.57	$\frac{3}{4}$	.2410	4.15

Continued on next page

CAPACITY OF HOLE					
Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel	Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel
7	.0476	21.02	16	.2487	4.02
¼	.0511	19.57	¼	.2565	3.90
½	.0546	18.32	½	.2645	3.78
¾	.0583	17.15	¾	.2725	3.67
8	.0622	16.08	17	.2807	3.56
¼	.0661	15.13	¼	.2890	3.46
½	.0702	14.25	½	.2975	3.36
¾	.0744	13.44	¾	.3060	3.27
9	.0787	12.71	18	.3147	3.18
¼	.0831	12.03	¼	.3235	3.09
½	.0877	11.40	½	.3324	3.01
¾	.0923	10.83	¾	.3415	2.93
10	.0972	10.29	19	.3507	2.85
¼	.1021	9.79	¼	.3599	2.78
½	.1071	9.34	½	.3694	2.71
¾	.1123	8.90	¾	.3789	2.64

Continued on next page

CAPACITY OF HOLE					
Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel	Hole Size Inches	Barrels Per Linear Foot	Linear Feet Per Barrel
11	.1175	8.51	20	.3885	2.57
¼	.1229	8.14			
½	.1285	7.78	22	.4701	2.13
¾	.1341	7.46			
			24	.5595	1.79
12	.1399	7.15			
¼	.1458	6.86	26	.6566	1.52
½	.1518	6.59			
¾	.1579	6.33	28	.7615	1.31

CAPACITY OF CASING					
Casing Size OD Inches	Weight Per Foot Complete	Casing ID Inches	Drift Dia. Inches	Barrels Per Foot	Feet Per Barrel
4 ½	11.60	4.000	3.875	.0155	64.34
	13.50	3.920	3.795	.0149	66.99
	15.10	3.826	3.701	.0142	70.32
5	11.50	4.560	4.435	.0202	49.51
	15.00	4.408	4.283	.0189	52.98
	18.00	4.276	4.151	.0178	56.30
5 ½	14.00	5.012	4.887	.0244	40.98
	15.00	4.950	4.825	.0238	42.01
	17.00	4.892	4.767	.0232	43.01
	20.00	4.778	4.653	.0222	45.09
	23.00	4.670	4.545	.0212	47.20
7	23.00	6.366	6.243	.0394	25.40
	26.00	6.276	6.151	.0383	26.14
	29.00	6.184	6.059	.0371	26.92
	32.00	6.094	5.969	.0361	27.72
	35.00	6.004	5.879	.0350	28.56
	38.00	5.920	5.795	.0340	29.37

Continued on next page

CAPACITY OF CASING					
Casing Size OD Inches	Weight Per Foot Complete	Casing ID Inches	Drift Dia. Inches	Barrels Per Foot	Feet Per Barrel
$7 \frac{5}{8}$	26.40	6.969	6.844	.0472	21.20
	29.70	6.875	6.750	.0459	21.778
	33.70	6.765	6.640	.0445	22.49
	39.00	6.625	6.500	.0426	23.45
$8 \frac{5}{8}$	24.00	8.097	7.972	.0637	15.70
	28.00	8.017	7.892	.0624	16.02
	32.00	7.921	7.796	.0609	16.41
	36.00	7.825	7.700	.0595	16.81
	40.00	7.725	7.600	.0580	17.25
$9 \frac{5}{8}$	40.00	8.835	8.679	.0748	12.19
	43.50	8.755	8.599	.0745	13.43
	47.00	8.681	8.525	.0732	13.66
	53.50	8.535	8.379	.0708	14.13
$10 \frac{3}{4}$	40.50	10.050	9.894	.0981	10.19
	45.50	9.950	9.794	.0962	10.40

Continued on next page

CAPACITY OF CASING					
Casing Size OD Inches	Weight Per Foot Complete	Casing ID Inches	Drift Dia. Inches	Barrels Per Foot	Feet Per Barrel
10 ³ / ₄	51.00	9.850	9.694	.0943	10.61
	55.50	9.760	9.604	.0925	10.81
	60.70	9.660		.0906	11.03
	65.70	9.560		.0888	11.26
11 ³ / ₄	47.00	11.000	10.844	.1175	8.51
	54.00	10.880	10.724	.1150	8.70
	60.00	10.772	10.616	.1127	8.87
13 ³ / ₈	54.50	12.615	12.459	.1546	6.47
	61.00	12.515	12.359	.1521	6.57
	68.00	12.415	12.259	.1497	6.68
16	55.00	15.375	15.188	.2296	4.35
	65.00	15.250	15.062	.2259	4.43
	75.00	15.125	14.936	.2222	4.50
	84.00	15.010	14.822	.2188	4.57
20	90.00	19.19	18.950	.3577	2.80
	94.00	19.124	18.936	.3553	2.81

DRILL COLLAR CAPACITIES AND DISPLACEMENTS (Bbls. Per Foot)						
OD	ID Cap.	2 .0039	2 ¼ .0049	2 ½ .0061	2 13/16 .0077	3 .0087
4 1/8"	Wt/ft	34.8	31.9	28.7		
	Displace	.0127	.0116	.0104		
4¾	Wt/ft	49.6	46.7	43.6		
	Displace	.0180	.0170	.0159		
5	Wt/ft	56.1	53.2	50.1		
	Displace	.0204	.0194	.0182		
6	Wt/ft	85.4	82.6	79.4	75.0	72.1
	Displace	.0310	.0301	.0289	.0273	.0262
6 ¼	Wt/ft	93.6	90.8	87.6	83.2	80.3
	Displace	.0341	.0330	.0319	.0303	.0292
6 ½	Wt/ft	102	99.3	96.1	91.7	86.8
	Displace	.0371	.0361	.0350	.0334	.0316
6 ¾	Wt/ft	111	108	105	101	97.6
	Displace	.404	.0393	.0382	.0367	.0355

Continued on next page

DRILL COLLAR CAPACITIES AND DISPLACEMENTS (Bbls. Per Foot)						
OD	ID Cap.	2 .0039	2 ¼ .0049	2 ½ .0061	2 13/16 .0077	3 .0087
7	Wt/ft Displace	120 .0437	117 .0426	114 .0415	110 .0400	107 .0389
7 ¼	Wt/ft Displace	130 .0473	127 .0462	124 .0451	119 .0433	116 .0422
7 ¾	Wt/ft Displace	150 .0546	147 .0535	144 .0524	139 .0506	136 .0495
8	Wt/ft Displace	160 .0582	157 .0571	154 .0560	150 .0546	147 .0535
9	Wt/ft Displace	206 .0749	203 .0739	200 .0728	195 .0709	192 .0699
10	Wt/ft Displace					243 .0884
11	Wt/ft Displace					299 .1088

DRILL PIPE CAPACITIES AND DISPLACEMENTS								
OD	Nom. Weight	Adj. Weight	ID	Tool Joint			Displacement BBL/FT	Capacity BBL/FT
				Connection	OD	ID		
2 $\frac{7}{8}$	10.40	10.37	2.151	S.H.	3 $\frac{3}{8}$	1 $\frac{3}{4}$	0.00375	0.00440
2 $\frac{7}{8}$	10.40	10.82	2.151	I.F.	4 $\frac{1}{8}$	2 $\frac{1}{8}$	.00391	.00449
3 $\frac{1}{2}$	13.30	13.51	2.764	S.H.	4 $\frac{1}{8}$	2 $\frac{1}{8}$	.00487	.00723
3 $\frac{1}{2}$	13.30	13.86	2.764	I.F.	4 $\frac{3}{4}$	2 $\frac{11}{16}$	.00500	.00740
4	14.00	14.29	3.340	S.H.	4 $\frac{5}{8}$	2 $\frac{9}{16}$	.00520	.01055
4 $\frac{1}{2}$	16.60	17.64	3.826	I.F.	6 $\frac{1}{8}$	3 $\frac{3}{4}$	.00634	.01419
4 $\frac{1}{2}$	16.60	17.94	3.826	H-90	6	3 $\frac{1}{4}$	.00648	.01394
4 $\frac{1}{2}$	20.00	22.33	3.640	E.H.	6 $\frac{1}{4}$	2 $\frac{1}{2}$	.00802	.01267
5	19.50	20.99	4.276	E.H.	6 $\frac{3}{8}$	3 $\frac{3}{4}$	.00754	.01746
5	25.60	27.17	4.000	E.H.	6 $\frac{1}{2}$	3 $\frac{1}{2}$	.00973	.01528

Continued on next page

DRILL PIPE CAPACITIES AND DISPLACEMENTS								
O.D.	Nom. Weight	Adj. Weight	I.D.	Tool Joint			Displacment BBL/FT	Capacity BBL/FT
				Connection	OD	ID		
Hevi-Wate (Drillco)								
3 ½	26	27	2.0625	I.F.	4 ¾	2 3⁄16	.00982	.0041
4	28	29	2.5625	E.H.	5 ¼	2 11⁄16	.01055	.0064
4 ½	42	43	2.750	E.H.	6 ¼	2 7⁄8	.01564	.0073
5	50	51.67	3.000	T.H.	6 ½	3 1⁄8	.01880	.0087

Volume between Drill Pipe and Casing = Capacity of Casing - drill pipe displacement - drill pipe capacity.

Example: 4 ½", 16.60 lb./ft, I.F. Drill Pipe inside 8 5/8", 24 lb./ft Casing

Volume between D.P. and Casing = .0637 - .00634 - .01419 = .0432 bbl/ft

Appendix F

LOST CIRCULATION SLURRIES AND BARITE PLUG GUIDELINES

Diaseal M. Slurry

Diaseal M is a diatomaceous earth material available from all mud companies. This slurry is an easily pumpable, stable, high solids slurry with a very high water loss. Sea water, salt water, or other solutions high in electrolyte concentration may be used in place of fresh water.

Approximately 10 lb./bbl of fibrous LCM or a blend of fibrous, flake, and granular materials such as Kwik Seal is usually added to the slurry. If this does not seal the loss zone, the particle size and amount of LCM may be increased.

Formula for preparing the Diaseal M slurry in fresh and salt water are as follows:

Continued on next page

FORMULA FOR PREPARING ONE BARREL DIASEAL M WEIGHTED SLURRY WITH FRESH WATER					WITH SATURATED SALT WATER				
DENSITY Lb./Gal.	DIASEAL M		BARITE	WATER	DENSITY	DIASEAL M		BARITE	WATER
	Pounds	Sacks	Sacks	Barrels	Lb./Gal.	Pounds	Sacks	Sacks	Barrels
9	50	1.00	0	0.93					
10	42.6	.85	0.6	0.90	10.5	46.5	.93	0	.940
11	38.9	.78	1.2	0.86	11	44.5	.89	.3	.920
12	35.8	.72	1.8	0.83	12	41.5	.83	.9	.880
13	32.7	.65	2.3	0.80	13	38.5	.77	1.6	.845
14	29.3	.59	2.9	0.76	14	35.5	.71	2.2	.810
15	26.5	.53	3.5	0.73	15	32.5	.65	2.8	.770
16	23.9	.48	4.0	0.69	16	29.5	.59	3.4	.740
17	21.0	.42	4.6	0.66	17	26.0	.52	4.0	.695
18	18.7	.37	5.2	0.62	18	23.0	.46	4.6	.660
19	16.4	.33	5.8	0.58					

Example:

100 bbl. Of 14.0 lb./gal. Diaseal M slurry
requires:

59 sx. Diaseal M
290 sx. Barite
76 bbl Water

Example:

100 bbl. of 14.0 lb./gal. Diaseal M slurry
with saturated salt water requires:

71 sx. Diaseal M
220 sx. Barite
81 bbl. Salt Water

High Fluid Loss - Attapulgate Slurry

A slurry of attapulgate is prepared with sufficient gel strength to support barite and then barite added to desired density. To this slurry, lost circulation materials (fibrous, flake, and granular) are added in amounts totaling about 30 to 50 lb./bbl. This slurry has a very high fluid loss, which causes particle dehydration of the slurry and formation of a compacted plug in the thief zone. A typical formula for 100 barrels of 18 lb./gal slurry is as follows:

- 6 sacks - Attapulgate
- 70 barrels - Fresh water
- 47,300 lb. - Barite
- 500 lb. - Coarse granular material (walnut shells)
- 500 lb. - Fine granular material (walnut shells)
- 500 lb. - Coarse flake material (mica)
- 500 lb. - Fine flake material (mica)
- 500 lb. - Coarse fibrous material (phenoseal)
- 500 lb. - Fine fibrous material (phenoseal)
- 500 lb. - Cane fiber

Continued on next page

FORMULA FOR ATTAPULGITE-BARITE SLURRY

Density	Water, bbl	Attapulgate, lb.	Gypsum, Lb.	Barite, Lb.	Water Required Per bbl Finished Slurry
8.8	1	25-30	1	0	.98
10	1	25-30	1	70	.955
11	1	20-25	1	148	.910
12	1	20-25	1	234	.864
13	1	20	1	310	.829
14	1	16-18	1	393	.792
15	1	15	1	485	.756
16	1	15	1	585	.719
17	1	10-12	1	696	.683
18	1	10-12	1	820	.652

Bentonite-Diesel Oil (Gunk Squeeze)

A typical "Gunk Squeeze" is prepared by mixing 3 to 4 sacks of bentonite per barrel of diesel oil. This is pumped down the drill pipe and as it is pumped out of the pipe the rams are closed. One barrel of mud is pumped down the annulus to each 4 barrels of gunk displaced from the drill pipe. When the gel mixes with the water in the mud, it swells and forms a solid plug.

Continued on next page

**Bentonite-Diesel
Oil (Gunk Squeeze)**
Continued

It is **important** that the gunk does not come up around the pipe. The drill pipe should be slowly reciprocated while the plug is being placed to avoid becoming stuck.

**Barite Plug
Guidelines -
Introduction**

If a formation breaks down during a well control operation or if lost returns causes a well kick, formation fluid can begin flowing into the annulus from the kick zone and into the zone of lost returns at an uncontrolled rate. This creates a well control situation which cannot be solved by conventional methods since the lost returns will not allow building the mud weight to the point required to shut off flow.

Usually, the first step in shutting off an underground flow is to spot a high density barite plug between the flowing and lost returns zones. The size of the plug that is spotted should be designed so that the resulting increase in hydrostatic pressure at the kick zone is large enough to shut off the flow and allow the barite to settle into a competent plug at the bottom of the hole. The settled plug will normally grow at a rate of one to three feet per hour. If the barite pill is spotted off bottom, the barite will settle below this point to a firm foundation which will stop further settling, usually the bottom of the hole. If the distance from where the pill is spotted to the bottom of the hole is too great, very little, if any, hard settled plug will result in a reasonable length of time.

Composition

A barite slurry normally consists of barite, fresh water, chrome lignosulfonate, and caustic. The purpose of the lignosulfonate and caustic is to deflocculate the slurry so that high density slurries (20 to 22 lb./gal) can be mixed and pumped and to increase the barite settling rate. Some types of barite are more difficult to deflocculate than others and will require more lignosulfonate. However, a typical barite slurry will require about 4 lb./bbl of lignosulfonate at temperatures up to 300°F and 8 lb./bbl of lignosulfonate at temperatures above 300°F. Enough caustic should be used to obtain a pH of 10 to 11. About one pound of caustic to every eight pounds of lignosulfonate will usually be required. At temperatures less than 180°F, SAPP can be used instead of lignosulfonate except in some very contaminated barites (usually red barite). Approximately 0.5 lb./bbl of SAPP and 0.25 lb./bbl caustic will be sufficient. The SAPP treated slurry has a much higher fluid loss than the lignosulfonate treated slurry, and may be preferred if the plug is to be spotted opposite a sand.

The density of the barite slurry to be used is not highly critical. First consideration should be given to obtaining a hydrostatic pressure sufficient to stop the flow into the annulus. Normally, a high density slurry (20-22 lb./gal) is preferred in order to achieve the necessary increase in hydrostatic pressure with a barite slurry column between

Continued on next page

Composition

Continued

the kick and loss zones. Although the barite settling rates are slightly higher in lower density slurries, this is not as important as achieving a kill weight column of fluid in the annulus. **Table I** below shows the amount of barite necessary to build slurries of various densities.

TABLE I		
Slurry Density lb/gal	Sacks Barite/ bbl of Final Slurry	Sacks Barite/ bbl of Water
19.0	5.88	9.79
19.5	6.16	10.58
20.0	6.43	11.42
20.5	6.71	12.32
21.0	6.98	13.29
21.5	7.26	14.32
22.0	7.53	15.44
22.5	7.81	16.64
23.0	8.08	17.94

A typical recipe for one barrel of 21 lb./gal barite slurry for use at temperatures less than 300°F is:

7.0 sacks of barite

0.525 barrels of water

4.0 pounds of Lignosulfonate (8 lb./bbl of water)

0.5 pounds of caustic (1 lb./bbl of water)

Mixing

When mixing barite slurries, it is necessary to use high energy jet mixing in order to dispense and wet the barite quickly. This must be done in order to achieve a smooth, minimum viscosity slurry and to attain the maximum desired density. The recirculating or low pressure mixers do not provide sufficient energy to allow mixing of high density barite slurries. The best mixer for this purpose is a Halliburton Twin-Jet mixer. (See **Figures 2** and **3**.) This mixer contains two replaceable jets. (See **Figure 4**.) The mix water should enter the jet hopper bowl at a pressure of 600-1000 psi in order to assure complete mixing of the barite. The mixing rate is set by the size of the jets that are used. Either No. 6 or No. 7 jets can be used. (See **Figures 5** and **6**.) Pressure-volume curves for various combinations of these two jets are shown in **Figure 7**. When mixing a 21 ppg barite slurry, the volume rate of the mixed slurry will be about twice the mix water pump rates shown on this figure. Assuming a 21 ppg barite slurry is being mixed at 600 psi jet pressure, the following appropriate mix rate will be attained with the various jet combinations:

Continued on next page

Mixing

Continued

Jets	Barite Slurry bbl/min
2, No. 6	10
1, No. 6 & 1, No. 7	8
2, No. 7	6
1, No. 6 & Blank	5
1, No. 7 & Blank	3

By increasing the jet pressure, some increase in mixing rates will be achieved. This mixer also has a mix water by-pass line. The slurry density is controlled by adjusting the amount of water by-passed around the jets. This will also have an effect on mix rate.

If only a recirculating cementing unit is available, it can be converted to use a jet mixer by coming directly off the high-pressure pump through a line to a twin jet mixer set on the ground. This modification can be done quickly if the twin-jet mixer is available.

The mix water should be prepared before beginning the barite mixing operation. The lignosulfonate should be added to the water and mixed thoroughly, followed by the caustic. Approximately twice the concentration of lignosulfonate and caustic required in the final slurry should be added to the mix water. Mixing of the lignosulfonate is best accomplished by use of a hopper.

Continued on next page

Mixing
Continued

The barite slurry should be pumped through the by-pass line until the desired density and consistency are obtained. The density should be checked with a pressurized mud balance and monitored continually during the mixing operation.

**Pumping and
Displacement**

Before beginning to mix the barite slurry, the equipment should be arranged similar to that shown in Figure 1. It is necessary to keep the barite slurry moving at all times so that plugging will not occur. The rig pump may be used to pump the slurry out of the drill string in case of a pump failure in the cementing unit.

The barite slurry should be mixed and pumped as fast as is practical. The rate at which the service company can mix should be investigated before beginning the job. A positive pressure should be maintained at the cementing head at all times in order to prevent the barite slurry from falling away. A pressure gauge may be installed at the cementing head so that the pressure can be monitored at all times.

When the barite slurry has been pumped into the drill pipe, it should be followed immediately by mud and displaced down the drill string. Provisions should be made to supply mud to the cementing unit at the required displacement rate. In an underground flow, the barite slurry must be pumped fast enough to minimize the mixing with the intruding fluid and the resulting reduction in slurry density.

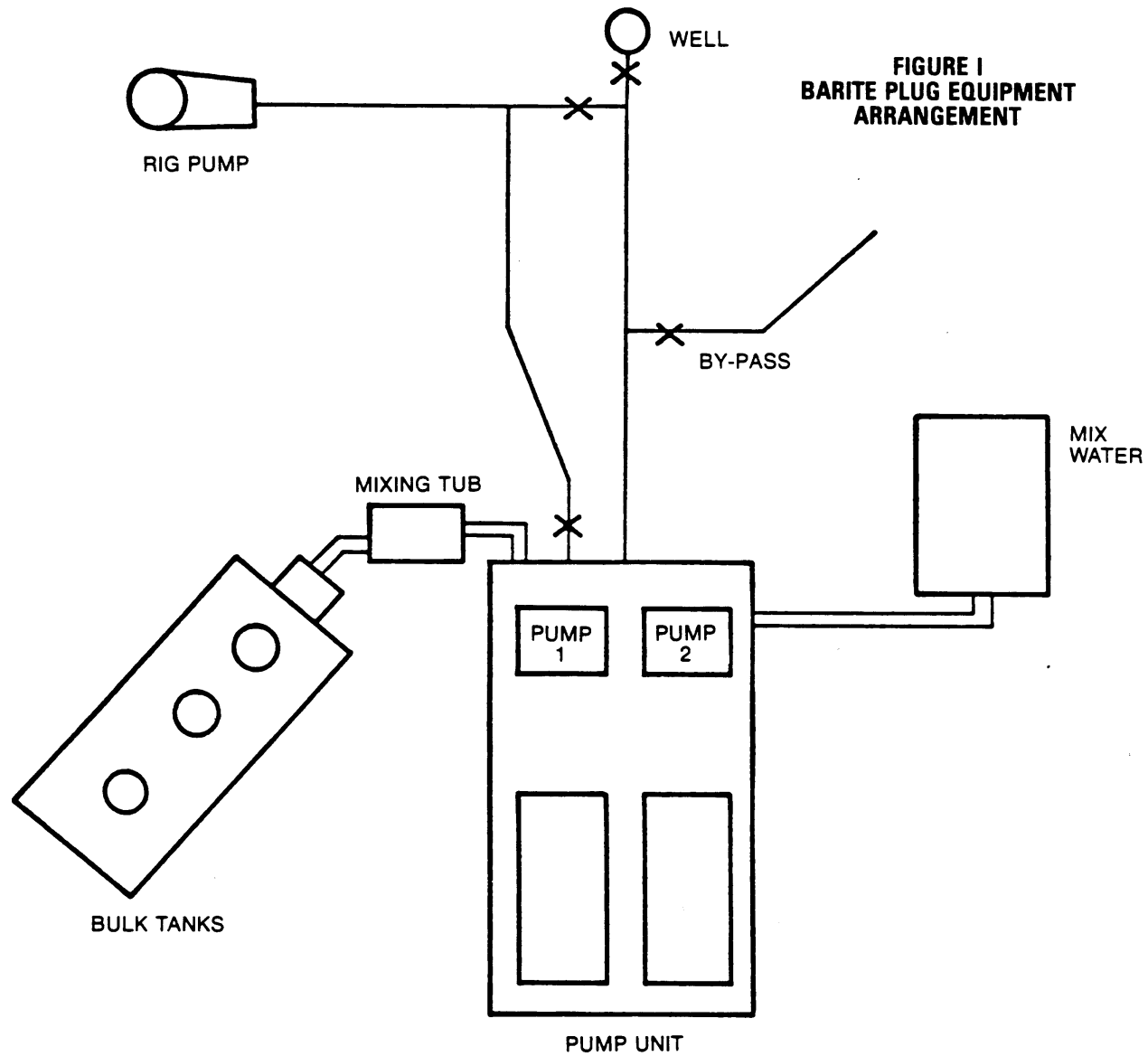
Types of Barite Plugs

Types of barite plugs can be divided into two categories:

1. **Balanced Plug** - When the pressure or volume of flow is not too great, a balanced plug can be spotted on bottom and the drill string pulled up above it. The well can then be checked for flow. If it is dead, allow time for the barite to settle into a plug and then proceed with the operation of logging, running casing, etc. The risks of pulling out of a long plug or plug set to control an underground blowout are high. If the well is not dead, you are not in good position to immediately set another plug. In the case of an underground blowout, a noise log and temperature survey will probably be required to determine if the well is flowing.
2. **“Barite-in” the Drill Collars** - When the pressure or flow are excessive and when there is doubt that the first plug will hold, we do not want to pull up above the plug. In these cases, we elect to sacrifice the bottom-hole assembly rather than pull above the plug and risk being trapped off bottom with the well still flowing.

In this case, the barite slurry is completely displaced from the drill string (over displace 3-5 bbl) and positive pressure maintained on the drill pipe so that the bit will not become plugged. In this manner, you are always prepared to set another plug in case the first one does not hold.

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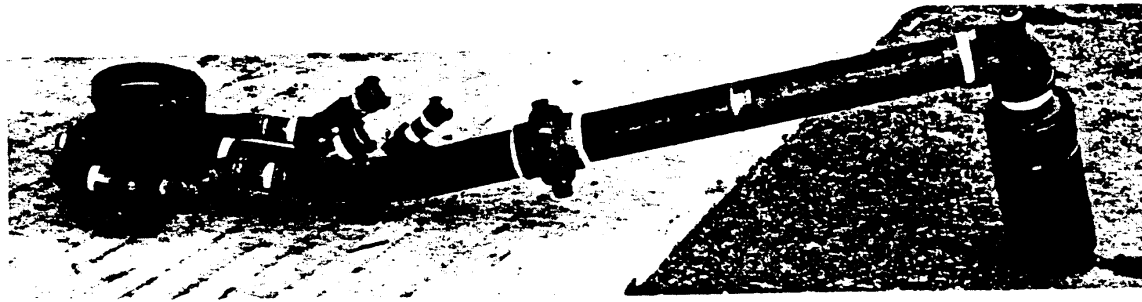


Figure 2

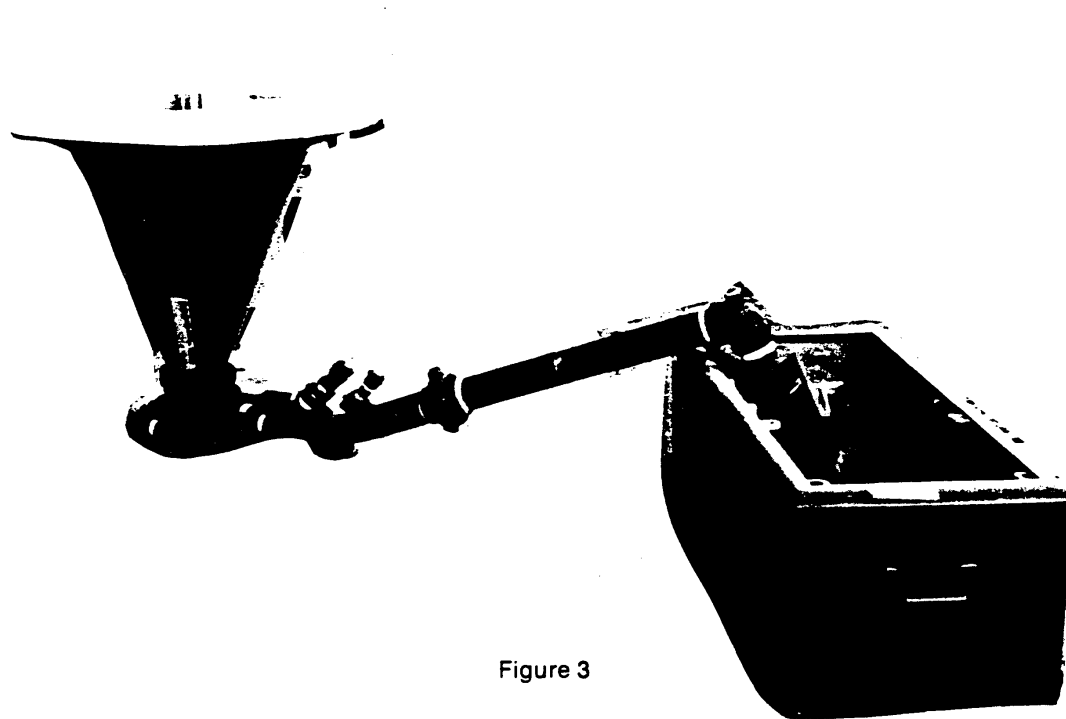


Figure 3

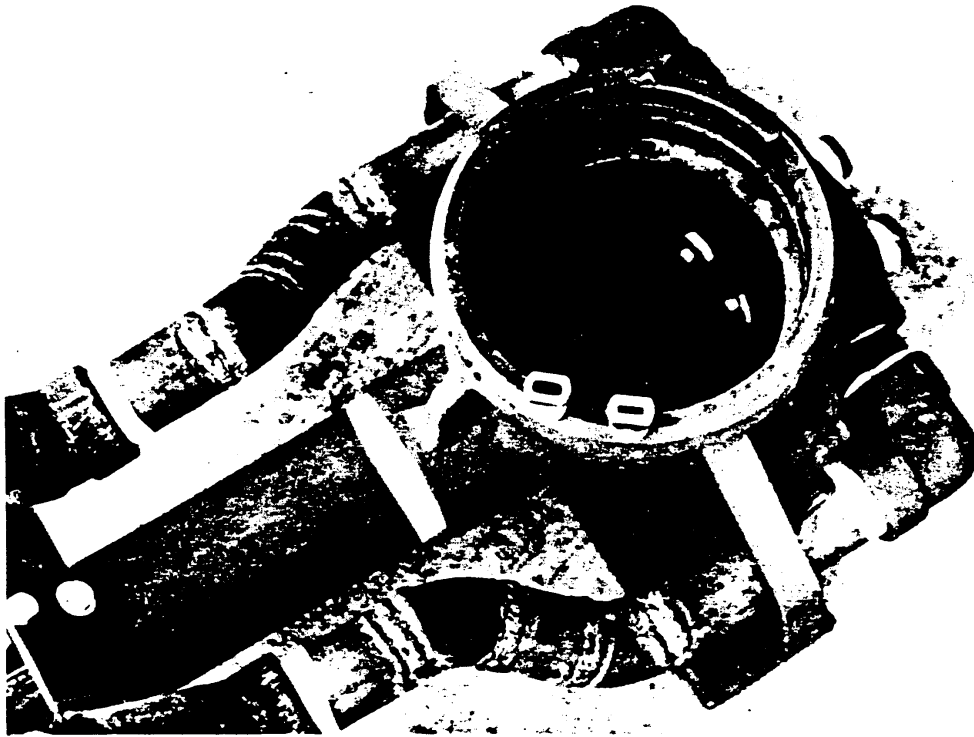


Figure 4

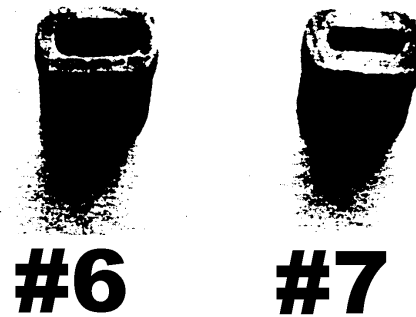


Figure 5

JETS FOR HIGH PRESSURE MIXER

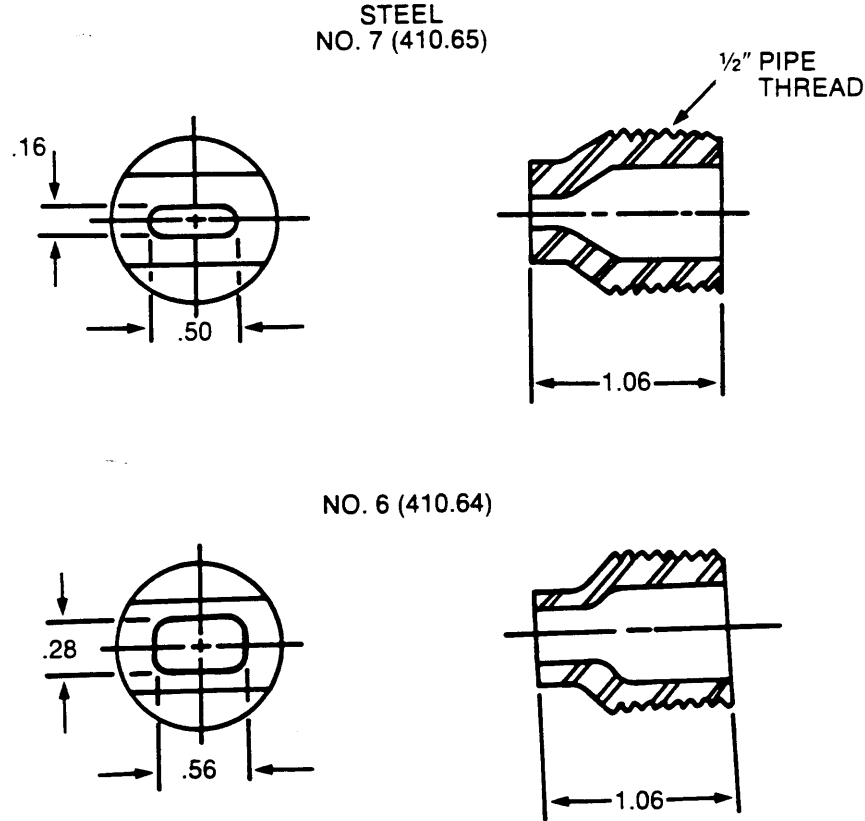


Figure 6

HALLIBURTON TWIN-JET MIXER

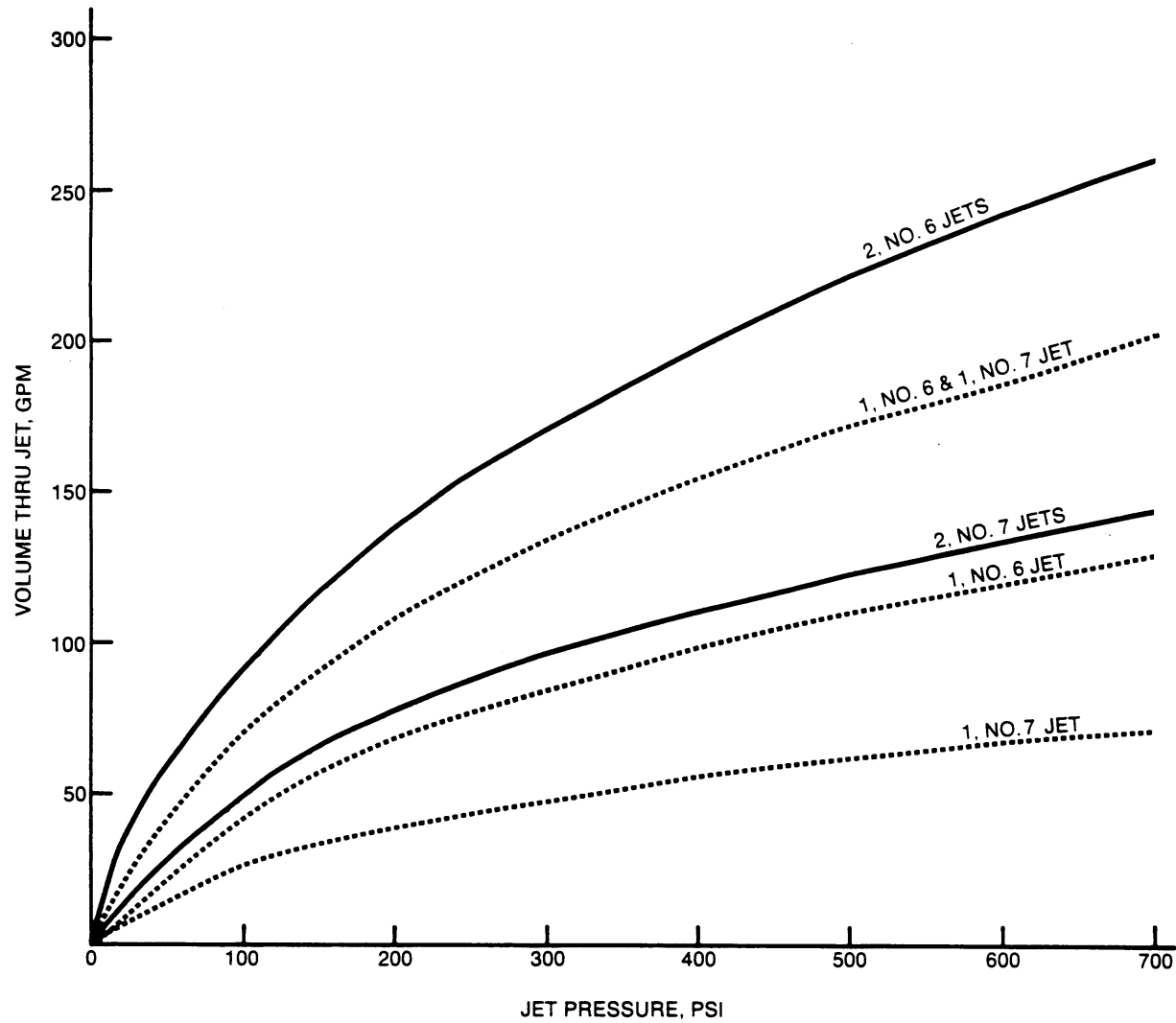


Figure 7

Appendix G

MISCELLANEOUS

CONVERSION TABLE

Linear

Centimeter	0.3937 inch
Inch	2.54 centimeter
Meter	3.281 feet
Meter	39.37 inches
Yard	0.9144 meters
Mile	5280 feet
Mile	1.609 kilometers

Area

Acre	43,560 sq. ft.
Square centimeter	0.155 sq. in.
Square inch	6.452 sq. cm.
Square mile	2.59 sq. km.

Weight

Gram	15.432 grains
Kilogram	2.2046 pounds
Ton (short)	2000 pounds
Ton (Metric)	2205 pounds
Ton (long)	2240 pounds

Density

g/cc	62.4282 lb./cu. ft.
g/cc	8.3454 lb./gal
lb./cu. ft.	7.48 lb./gal
lb./bbl	g/350 cc
Specific gravity	lb./gal X 0.12

Continued on next page

CONVERSION TABLES

Continued

Volume

Barrel	42 gallons
Barrel	5.6146 cu. ft.
Cubic centimeter	0.061 cu. in.
Cubic foot	7.4805 gallons
Cubic inch	16.387 cu. Cm.
Cubic meter	6.2897 bbl
Gallon	231.0 cu. in.
Gallon	3.7853 liters

Flow Rate

BBL/hr.	0.70 gal/min.
BBL/hr.	0.0936 cu. ft./min.
Cu. ft./min.	7.48 gal/min.
Gal/min.	1.4286 bbl/hr.
Gal/min.	69.09 cc/sec.

Temperature

$$T^{\circ}\text{F} = \frac{9}{5}(T^{\circ}\text{C}) + 32$$

$$T^{\circ}\text{C} = \frac{5}{9}(T^{\circ}\text{F} - 32)$$

Pipe Weight, lb./ft X 0.0003638 = Displacement, bbl/ft

FILTRATION EQUATIONS

Static Filtration Equation

$$V_f = A \left[\frac{2k \left(\frac{C_c}{C_m} - 1 \right) \Delta P t}{\mu} \right]^{1/2}$$

Where:

V_f	=	Volume of filtrate
A	=	Filtration area
C_c	=	Volume fraction of solids in cake
C_m	=	Volume fraction of solids in mud
ΔP	=	Filtration Pressure
t	=	Filtration time
μ	=	Viscosity of filtrate

Cake Thickness

$$h = \frac{V_f}{A \left(\frac{C_c}{C_m} - 1 \right)}$$

FILTRATION EQUATIONS

Continued

Cake Permeability

$$k \frac{V_f \times h \times \mu}{\Delta P} \times 9.04 \times 10^{-3}$$

Where:

- k = Permeability in millidarcies
 - V_f = Fluid loss in cc/7 sq. in/30 min.
 - h = Cake thickness in millimeters
 - μ = Filtrate viscosity in cp.
 - ΔP = Filtration pressure in psi
-

Volume Fraction Solids in Cake

$$C_c = \left(\frac{V_f}{h} \times 0.2214 + 1 \right) C_m$$

Where:

- V_f = Filtrate volume, cc/7 sq. in.
 - h = Cake thickness, mm
-

Particle Slip Velocity Equations

The difference in velocity of a particle and the average fluid velocity in a flowing stream is the particle slip velocity. This number is an indicator of the lifting capacity of a fluid.

The slip velocity can be approximated by the following three equations* which depend on the particle Reynolds Number.

1.
$$V_s = \frac{498 D_p^2 (W_p - W_m)}{\mu} \text{ for } R_p < 1$$
2.
$$V_s = \frac{175 D_p (W_p - W_m)^{.667}}{W_m^{.333} \mu^{.333}} \text{ for } R_p = 10 \text{ to } 100$$
3.
$$V_s = 113.4 \left[\frac{D_p (W_p - W_m)}{1.5 W_m} \right]^{1/2} \text{ for } R_p > 200$$

Where:

- V_s = Slip velocity in ft/min
- D_p = Particle diameter in inches
- W_p = Particle density in lb./gal
- μ = Mud viscosity at shear rate in flow stream
- R_p = Reynolds number = $\frac{15.45 W_m V_s D_p}{\mu}$

Continued on next page

**Particle Slip
Velocity Equations**
Continued

Equation 1 applies only to very slow rates of settling or slip velocity in laminar flow. Equation 3 applies to cases where the flow is turbulent around the particles and Equation 2 applies to the transition range between laminar and turbulent.

When there is doubt about which equation to use, the one giving the lowest slip velocity should be used.

*Equations from Preston L. Moore, "Drilling Operations Manual"
